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Design of Self-Supporting Surfaces with Isogeometric Analysis

Yang Xia^{a,b,*}, Angelos Mantzaflaris^{c,f}, Bert Jüttler^{d,c}, Hao Pan^e, Ping Hu^a, Wenping Wang^{b,*}

^a*School of Automotive Engineering, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, P.R. China*

^b*Department of Computer Science, The University of Hong Kong*

^c*Johann Radon Institute for Computational and Applied Mathematics (RICAM), Austrian Academy of Sciences*

^d*Institute of Applied Geometry, Johannes Kepler University, Linz, Austria*

^e*Microsoft Research Asia*

^f*Université Côte d'Azur, Inria Sophia Antipolis - Méditerranée, 2004 route des Lucioles, B.P. 93, 06902 Sophia Antipolis, France*

Abstract

Self-supporting surfaces are widely used in contemporary architecture, but their design remains a challenging problem. This paper aims to provide a heuristic strategy for the design of complex self-supporting surfaces. In our method, non-uniform rational B-spline (NURBS) surfaces are used to describe the smooth geometry of the self-supporting surface. The equilibrium state of the surface is derived with membrane shell theory and Airy stresses within the surfaces are used as tunable variables for the proposed heuristic design strategy. The corresponding self-supporting shapes to the given stress states are calculated by the nonlinear isogeometric analysis (IGA) method. Our validation using analytic catenary surfaces shows that the proposed method finds the correct self-supporting shape with a convergence rate one order higher than the degree of the applied NURBS basis function. Tests on boundary conditions show that the boundary's influence propagates along the main stress directions in the surface. Various self-supporting masonry structures, including models with complex topology, are constructed using the presented method. Compared with existing methods such as thrust network analysis and dynamic relaxation, the proposed method benefits from the advantages of NURBS-based IGA, featuring smooth geometric description, good adaption to complex shapes and increased efficiency of computation.

Keywords:

Masonry structure, Self-supporting, Isogeometric analysis, Equilibrium approach, Architectural geometry

1. Introduction

Masonry is a type of architecture built from bricks or stones that are laid in and bound together by mortar. It has been used for centuries and is regarded as one of the most important architectural

*Corresponding author

Email addresses: yangxia@dlut.edu.cn (Yang Xia), wenping@cs.hku.hk (Wenping Wang)

4 forms. At present masonry is still widely used throughout the world, especially in low- and mid-
5 rise buildings for its economical competitiveness and aesthetic value [1]. Masonry surfaces are
6 a fascinating form of masonry that features a large structural span and various shapes, including
7 arches, domes and vaults (see Fig. 1 for examples). The intrinsic characteristic of a masonry
8 surface is that it is self-supporting, which means the surface bears the weight of the units, usually
bricks or stones, and maintains the equilibrium state with minimum support only on the borders.

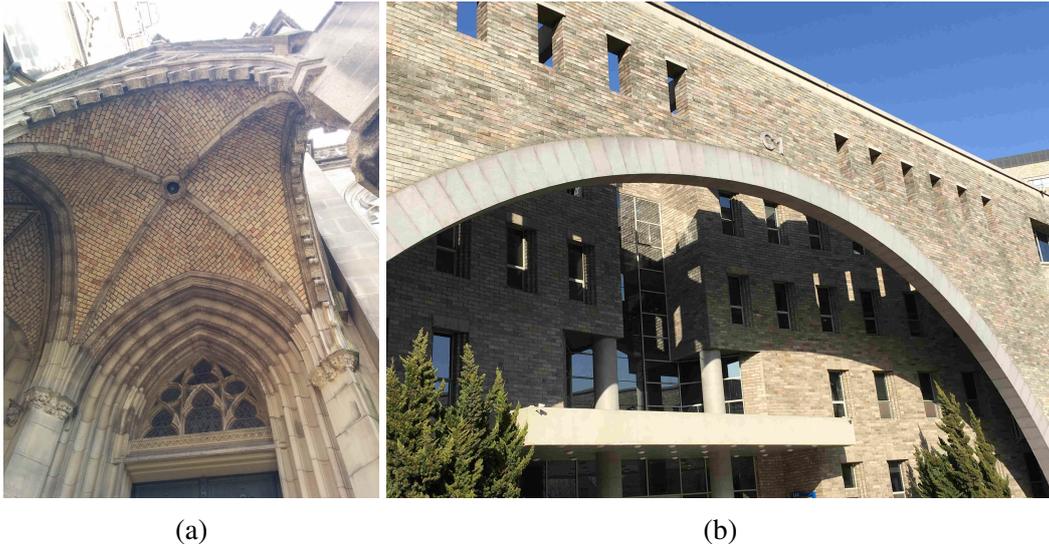


Figure 1: Masonry architectures with self-supporting surfaces. (a) A typical quadripartite vault at an entrance of Mariendom, Linz. (b) A modern building with a grand arch in Dalian.

9
10 Despite the long history and wide use of masonry structures, the design of self-supporting
11 surfaces remains a challenge. The difficulty is rooted in the building material of masonry, which
12 is composed of discrete units, such as stones or bricks. The units are held together almost all by
13 themselves except for the constraint on the boundary to resist gravity, therefore the geometrical
14 configuration needs to be carefully designed to keep the discrete units together and maintain the
15 structure's shape. Robert Hook first discovered that the ideal shape of a masonry arch is analogous
16 to an inverted catenary curve. This discovery has been applied to the design and assessment of
17 masonry buildings, e.g., in Giovanni Poleni's study of St. Peter in the Vatican [2], and is still
18 an influential guide to modern design [3]. Classical designs of self-supporting surfaces are based
19 on empirical rules and various codes of practices, and the majority of contemporary designs are
20 duplications of existing structures from history. However, contemporary architects have shown
21 increasing interests in building new masonry structures with complex topology, which necessitates
22 the development of new design methods.

23 We propose a heuristic strategy for the design of self-supporting masonry surfaces with com-
24 plex geometry and topology. Specifically, we study the characteristic equilibrium state with the
25 membrane shell theory. The Airy stress function is further used to transform the equilibrium
26 equations into a single partial differential equation relating the Airy stress and the height func-
27 tion representing a self-supporting surface. Computationally, the nonlinear isogeometric analysis

(IGA) method is applied for solving the equilibrium equation, in order to obtain the self-supporting surfaces. The IGA-based method produces an accurate solution with the convergence rate being one order higher than the degree of the NURBS basis used. To summarize, the contributions of this work are:

1. An equilibrium state modeled with IGA is proposed for self-supporting surfaces. Surfaces with complex topology are represented by multi-patch NURBS with high smoothness.
2. A heuristic strategy to design self-supporting surfaces is provided by tuning the Airy stress of the surfaces.
3. Newton's iteration is used to solve the nonlinear changes of gravity load caused by shape variation.

1.1. Related work

Equilibrium. The state of equilibrium is a fundamental consideration for designing self-supporting structures. Influenced by the classic inverted catenary curve theory, numerical methods have been developed to describe the equilibrium state of self-supporting shapes. The thrust lines method (TLM) is proposed to consider the thrust lines as the centers of thrust forces. To maintain structural equilibrium, thrust lines must be contained within the masonry structure. Thrust line analysis is used to assess various masonry buildings [4] and constitutes the traditional equilibrium approach to calculate masonry structures [5]. Thrust network analysis (TNA), proposed by Block et al. [6, 7], assumes that a network of forces exists in the masonry and the structure is stable once the forces maintain equilibrium. The TNA method discretizes the surface into a network and models the equilibrium of the surface as the balance of forces on the network nodes. TNA enables the modeling of complex masonry structures [8], based on which form-finding and design algorithms have been proposed [9]. Liu et al. [10] define a new parameterization for the space of self-supporting triangular meshes, based on which the force distributions can be optimized. An optimal assembling process of building blocks is proposed by Deuss et al. [11] to guide the physical construction of self-supporting structures. Bletzinger et al. studied the simulation of stress states of masonry structures and the numerical methods for simulation are merged into the form-finding and structural optimization [12–14].

Geometric representation. Triangular or polygon meshes are used in TLM and TNA methods, which have considerable discretization errors in shape representation. Miki et al. [15] introduced NURBS for the geometric representation of masonry structures. The spline-based geometric description represents an advantage over the mesh-based models used in TNA-related methods because they have better smoothness and more regular geometry variation.

Material. A masonry structure is composed completely of bricks or stone blocks held together by external forces, typically gravity. It can resist large compressive stress caused by its own gravity and outer loads but has almost no resistance to tension force [16]. Performing an accurate analysis on this type of bimodulus material is still a challenging problem in mechanics [17, 18]. In classical assumptions on the behavior of masonry structures, the complex material property of masonry is simplified and is considered as the ideal tension-free elastic material that does not fail under pressure [19, 20].

68 **Isogeometric analysis.** Isogeometric analysis (IGA) was first proposed by Hughes et al. [21]
69 as a numerical simulation method to link the computer-aided design and simulation. In the present
70 work, IGA is used for simulating self-supporting shapes for two benefits. First, in IGA the smooth
71 geometry defined by NURBS describes the masonry surface more accurately. Second, IGA offers
72 a rigorous framework for simulating the mechanics of masonry and the equilibrium state of the
73 surface, which is a distinct advantage over the network-based TNA methods. Simulation of shell
74 structures with IGA has been widely investigated to calculate the inner stress state of shells under
75 outer loads [22–24]. Cazzani et al. applied a NURBS based isogeometric beam model to simulate
76 the historical masonry arches [25]. Bletzinger et al. pioneered the research on designing self-
77 supporting surfaces for architecture design using isogeometric analysis. They applied the isoge-
78 ometric B-Rep to structural analysis and form-finding of structural membranes, and proposed the
79 updated reference strategy for form-finding with isogeometric membrane and beam elements [26–
80 29]. The design of architectural membranes with isogeometric elements is proposed in [26] for the
81 first time, proposing the updated reference strategy for the form-finding of membranes. In [28]
82 this method is expanded to form-finding of complex models described by untrimmed and trimmed
83 multi-patch geometries, as summarized in [27]. A special isogeometric Bernoulli beam element
84 embedded into a membrane structure was proposed in [29] for analyzing curves in the structure.
85 The dynamic relaxation method is applied for masonry design [30]. In these works the isoge-
86 ometric concept is used along with the form-finding algorithm to design self-supporting surfaces.
87 The form-finding is the inverse problem of classical structural analysis, and the main challenge in
88 form-finding is the handling of a singular stiffness matrix. In the present paper we also apply the
89 isogeometric analysis for structure simulation by proposing a direct design strategy to compute
90 the stresses in the masonry structure. Our method is effective in obtaining self-supporting shapes
91 compared with the form-finding strategy.

92 1.2. Outline

93 This paper is organized as follows. In Section 2, we introduce the theory of self-supporting
94 structures. In Section 3, we first present the heuristic design method using admissible Airy stress
95 states, and then construct the computational model based on IGA. In Sections 4 and 5, results and
96 discussions are given. Finally Section 6 concludes the paper.

97 2. Self-supporting membrane shell theory

98 2.1. Geometry

Three-dimensional shell structures are generally represented by their middle surfaces [31].
Based on Monge’s description (Figure 2), a surface

$$S = \{(x, y, h(x, y)) : (x, y) \in U\}$$

can be represented as a height function $h(x, y)$ over a two-dimensional (2D) domain U with Carte-
sian coordinates x and y :

$$\mathbb{R} \supset \begin{array}{l} U \\ (x, y) \end{array} \rightarrow \begin{array}{l} \mathbb{R} \\ h(x, y) \end{array} \quad (1)$$

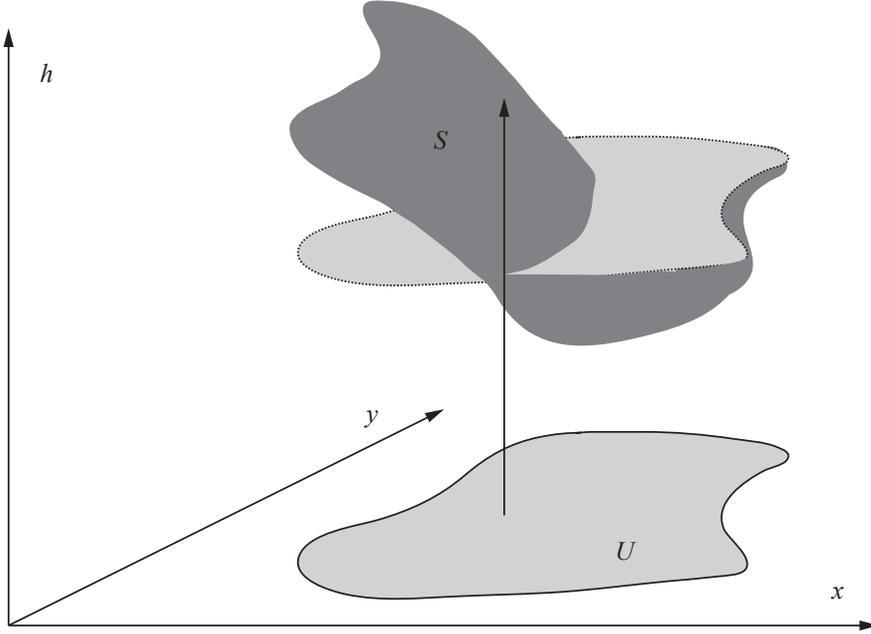


Figure 2: Monge's description of a masonry shell surface.

99 With this formulation, it is assumed that the masonry structure under consideration does not have
 100 any overhangs.

With IGA the 2D physical geometric domain U and the height function $h(x, y)$ are both described by the same set of NURBS basis functions. In particular, a tensor product parameter domain Ω is set for each NURBS patch by the knot vectors. Denote the knot intervals in each of the parametric dimensions as (ξ_1, ξ_2) and (η_1, η_2) , and we have Ω as $(\xi_1, \xi_2) \times (\eta_1, \eta_2)$. The geometry mapping using NURBS links the physical and parameter domains:

$$x = \sum_{i=1}^n \sum_{j=1}^m R_{i,j}(\xi, \eta) x_{i,j} \quad y = \sum_{i=1}^n \sum_{j=1}^m R_{i,j}(\xi, \eta) y_{i,j} \quad (2)$$

101 where $(x, y) \in U$, $(\xi, \eta) \in \Omega$, $R_{i,j}$ represents the 2-D NURBS bases and $x_{i,j}, y_{i,j}$ denotes the co-
 102 ordinates of control points, and n and m are the number of control points in the two directions.
 103 The geometry mapping in Eq. 2 defines a parameterization of the physical domain U over the
 104 parameter domain Ω .

Hence, the height function h over the physical domain U in Eq. 1 is also parameterized by $(\xi, \eta) \in \Omega$. Here we assume that the geometric mapping between parameter space and physical space is invertible. Furthermore, we assume that the height function $h(x, y)$ is given in the following NURBS form over the parameter domain.

$$h = \sum_{i=1}^n \sum_{j=1}^m R_{i,j}(\xi, \eta) h_{i,j} \quad (3)$$

where $R_{i,j}$ represents the 2-D NURBS bases and $h_{i,j}$ denotes the height of the control points. n and m are the number of control points in the two directions. To calculate the derivatives of height to x

and y , the geometry mapping in Eq.2 is used. Conceptually, the height function can be expressed as

$$h = \sum_{i=1}^n \sum_{j=1}^m \mathbf{R}_{i,j}(\xi(x,y), \eta(x,y)) h_{i,j} \quad (4)$$

105 2.2. Equilibrium analysis with membrane shell theory

Membrane theory is used to describe the balance conditions relating the surface geometry and the stress field on the surface which resists external loads [19, 32]. The stress per surface point when projected onto the horizontal plane is encoded by the symmetric 2×2 matrix

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \bar{N}_x & \bar{N}_{xy} \\ \bar{N}_{xy} & \bar{N}_y \end{bmatrix} \quad (5)$$

where \bar{N}_x , \bar{N}_y and \bar{N}_{xy} are the projected stress forces in the normal and shear directions respectively. The shell membrane equilibrium can be expressed by the following second-order differential equations [33]:

$$\begin{aligned} \frac{\partial \sigma_{11}}{\partial x} + \frac{\partial \sigma_{12}}{\partial y} &= 0 \\ \frac{\partial \sigma_{12}}{\partial x} + \frac{\partial \sigma_{22}}{\partial y} &= 0 \end{aligned} \quad (6)$$

$$\sigma_{11} \frac{\partial^2 h}{\partial x^2} + 2\sigma_{12} \frac{\partial^2 h}{\partial x \partial y} + \sigma_{22} \frac{\partial^2 h}{\partial y^2} = -\bar{P}_z \quad (7)$$

where \bar{P}_z is the gravitational load on the surface

$$\bar{P}_z = P_z \sqrt{1 + \left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2} \quad (8)$$

106 $P_z = \rho g t$ is the unit area load, where ρ is the density of the material, g is the gravitational acceler-
 107 ation, and t is the thickness of the surface. Assuming a uniform material density, without loss of
 108 generality, we use a constant $P_z = 1$ for subsequent discussions. Eq. 6 represents the horizontal
 109 equilibrium, which is equivalent to the stress tensor σ being divergence free. Eq. 7 represents the
 110 vertical equilibrium under external load.

For a simply connected domain, if there exists a function $\Phi(x, y)$ such that

$$\sigma_{11} = \frac{\partial^2 \Phi}{\partial y^2}, \quad \sigma_{22} = \frac{\partial^2 \Phi}{\partial x^2}, \quad \sigma_{12} = -\frac{\partial^2 \Phi}{\partial x \partial y}, \quad (9)$$

the divergence free property of σ (Eqs. 6) is satisfied. The function $\Phi(x, y)$ is called the Airy stress function, as discussed in Ref. [34] (page 26, Chapter 2). Substituting Eq. 9 into Eq. 7, we obtain the following equilibrium equation in the vertical direction:

$$\frac{\partial^2 h}{\partial y^2} \frac{\partial^2 \Phi}{\partial x^2} - 2 \frac{\partial^2 h}{\partial x \partial y} \frac{\partial^2 \Phi}{\partial x \partial y} + \frac{\partial^2 h}{\partial x^2} \frac{\partial^2 \Phi}{\partial y^2} = -\bar{P}_z \quad (10)$$

The equilibrium equation can be transformed into a dimensionless form. Let L_0 be the reference length. The coordinates x and y and the thickness of surface t can be expressed by their dimensionless forms x^* , y^* and t^* .

$$x = x^*L_0, \quad y = y^*L_0, \quad h = h^*L_0, \quad t = t^*L_0$$

The resultant stresses can be divided by L_0P_z to give the dimensionless forms,

$$\sigma_{22}^* = \sigma_{22}/(L_0P_z), \quad \sigma_{12}^* = \sigma_{12}/(L_0P_z), \quad \sigma_{11}^* = \sigma_{11}/(L_0P_z)$$

The dimensionless form of equilibrium equation is

$$\sigma_{22}^* \frac{\partial^2 h^*}{\partial y^{*2}} + 2\sigma_{12}^* \frac{\partial^2 h^*}{\partial x^* \partial y^*} + \sigma_{11}^* \frac{\partial^2 h^*}{\partial x^{*2}} = -\sqrt{1 + \left(\frac{\partial h^*}{\partial x^*}\right)^2 + \left(\frac{\partial h^*}{\partial y^*}\right)^2} \quad (11)$$

111 With the dimensionless form, the influence of stress states on the corresponding shapes can be
 112 clearly demonstrated. Therefore in the following solution with IGA, L_0 and P_z are set as unit
 113 values and the generality of the resulting shapes is not affected. This is useful in choosing the
 114 parameters of Airy stress functions for the design of masonry surfaces.

115 An issue related to Eq. 9 is that, Eq. 6 is more general than Eq. 9, because divergence free
 116 stress tensors exist that are not second-order differentials of a function. Indeed, by the Hodge
 117 decomposition theorem [35], a divergence free vector field may contain an additional component
 118 of a harmonic vector field which may not be integrable on a domain with high genus. Nevertheless,
 119 the present approach focuses on designing the Airy stress function which is able to describe a wide
 120 range of stress states in masonry structures.

121 2.3. Self-supporting condition of masonry structures

In this work, we assume that the material of masonry reacts elastically to arbitrary compression but cannot bear the slightest traction. Therefore, the elasticity theory of masonry can be characterized by the requirement that, in addition to the above equilibrium equations, the resultant stress tensor σ be negative semi-definite to ensure compression only:

$$\begin{aligned} \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} &\leq 0 \\ \frac{\partial^2 \Phi}{\partial x^2} \frac{\partial^2 \Phi}{\partial y^2} - \left(\frac{\partial^2 \Phi}{\partial x \partial y}\right)^2 &\geq 0 \end{aligned} \quad (12)$$

122 In other words, the self-supporting condition implies that Φ is concave [32].

123 3. Designing and computation self-supporting surfaces

124 3.1. Designing self-supporting surfaces by tuning Airy stress

125 The Airy stress and height functions are the two unknowns to be solved in the design of self-
 126 supporting surfaces. With the prescribed Airy stress, equilibrium in the horizontal directions is

127 fulfilled automatically. The unknown left is the height function of the masonry structure, which
 128 should meet the equilibrium condition in the vertical direction. Designing various self-supporting
 129 shapes can thus be achieved by adjusting the Airy stresses. The problem to be solved is formulated
 130 as follows: given the planar boundary curves of a shape, find a smooth surface with a specific
 131 inner stress state, such that the self-supporting equilibrium under the given loads and boundary
 conditions is fulfilled. The design strategy is illustrated in Fig. 3.

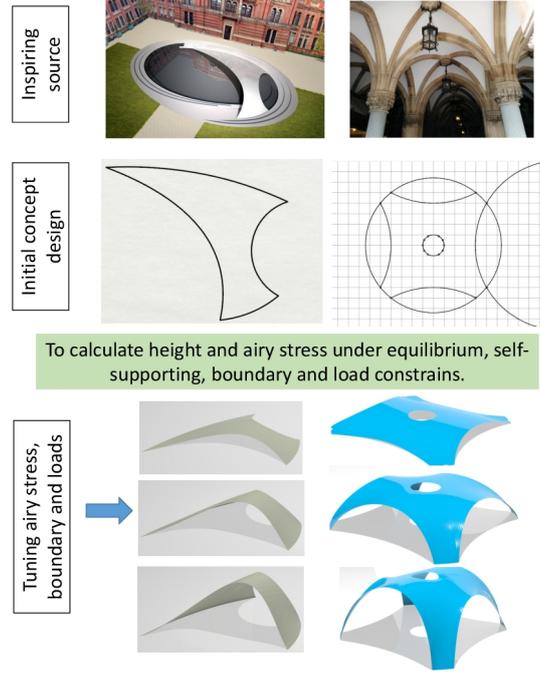


Figure 3: General problem description and design strategy. The sources of inspiration for the initial design shown in the picture include the sculpture “Crest” designed by Zaha Hadid Architects, and an indoor masonry vault roof. The picture of Crest is credited by the Zaha Hadid Architects.

132 Usually, the initial designs are simple curves that represent the boundaries of architectures and sculptures. With the proposed design strategy, the Airy stress function is prescribed, for which a particularly useful case is when the resultant stresses throughout the masonry shell are uniform [33], so that all points in the structure have the same inner stress and are equally strong for a single material. Such a situation represents an optimal state, as the structure can resist the largest total load without exceptional weak parts. The Airy stress function corresponding to the constant resultant stress state can be described as

$$\Phi = \frac{1}{2}\sigma_{22}^c x^2 + \frac{1}{2}\sigma_{11}^c y^2 - \sigma_{12}^c xy \quad (13)$$

where σ_{11}^c , σ_{12}^c and σ_{22}^c are constants. The corresponding stress tensor is

$$\sigma = \begin{bmatrix} \sigma_{11}^c & \sigma_{12}^c \\ \sigma_{12}^c & \sigma_{22}^c \end{bmatrix} \quad (14)$$

133 A linear polynomial $c_1x+c_2y+c_3$ can be added to the Airy stress function with arbitrary coefficients
 134 c_i , $i = 1, 2, 3$. Because the linear term does not affect the obtained stress, it is omitted. The
 135 concave condition of the Airy stress function can be easily obtained by assigning values such that
 136 $\sigma_{11}^c + \sigma_{22}^c \leq 0$ and $\sigma_{11}^c \sigma_{12}^c - \sigma_{22}^c{}^2 \geq 0$ (Eq. 12). If σ_{12}^c is set to zero, then the normal Airy stresses
 137 represent the major stress states, which can give meaningful directions for the design.

138 3.2. Computational modeling of self-supporting surfaces with IGA

139 Following the IGA framework, the non-uniform rational B-spline (NURBS) is used to describe
 140 the geometry of a self-supporting surface in the sense of Eq. 4. The shapes of masonry structures,
 141 such as domes and vaults, are generally composed of smooth surfaces, so can be accurately de-
 142 scribed by NURBS.

143 The designed planar footprint of the target self-supporting surface is given as input; During de-
 144 sign computation, the footprint remains fixed and only the B-spline coefficients are varied (Eq. 3).
 145 Depending on its complexity, the footprint domain is described by single or multiple NURBS
 146 patches. For example, in the ‘‘Crest’’ model, the input geometry is described by a single NURBS
 147 patch (Fig. 4(a)). The ‘‘Tent’’ model consists of multiple patches (Fig. 4(b)), where neighboring
 148 patches share control points along their common boundaries, which makes the whole shape always
 149 continuous. Through this setting the continuity of the multi-patch surface is C^0 , which suits for the
 150 design of masonry structures because kinks widely exist in the masonry buildings (see Fig. 1(a)
 for an example). To achieve higher order continuity, the algorithms in Refs. [36–38] can be used.

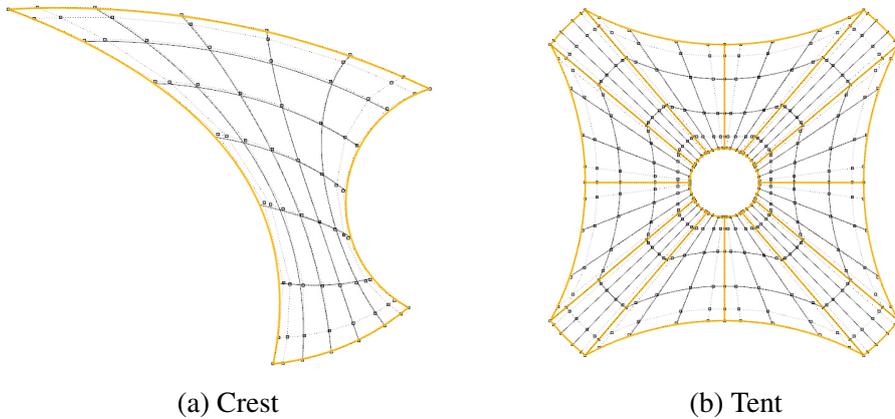


Figure 4: The input NURBS surface for calculating two masonry structures. The crest model is described by a single patch and the tent model by multiple patches.

151 The equilibrium equation (Eq. 10) is a second-order partial differential equation. NURBS based IGA [21] is used to solve the equation and calculate the self-supporting surfaces. A self-supporting surface generally has fixed or free boundary conditions, which can be easily implemented in the formulation of IGA by assigning Dirichlet boundary conditions. Permanent and static loads, especially the gravity, are deemed as Neumann boundary condition and discretized as the right-hand-side forces in IGA. The advantage of using IGA for computing masonry equilibrium is its high precision, for modeling various self-supporting shapes with different topological

and geometric characteristics and boundary conditions. In particular, with IGA we construct the weak form of Eq. 10:

$$\begin{aligned} & \left[\sigma_{11} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial x} \frac{\partial \mathbf{R}}{\partial x} d\Omega + 2\sigma_{12} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial y} \frac{\partial \mathbf{R}}{\partial x} d\Omega + \sigma_{22} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial y} \frac{\partial \mathbf{R}}{\partial y} d\Omega \right] \cdot \mathbf{h}^e \\ & = -P_z \int_{\Omega_e} \mathbf{R} \sqrt{1 + \left[\left(\frac{\partial \mathbf{R}}{\partial x} \cdot \mathbf{h}^e \right)^2 + \left(\frac{\partial \mathbf{R}}{\partial y} \cdot \mathbf{h}^e \right)^2 \right]} d\Omega \end{aligned} \quad (15)$$

Here, referring to Equations 3 and 4, we have

$$\begin{bmatrix} \frac{\partial \mathbf{R}}{\partial x} \\ \frac{\partial \mathbf{R}}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial \mathbf{R}}{\partial \xi} \\ \frac{\partial \mathbf{R}}{\partial \eta} \end{bmatrix}.$$

Eq. 15 can be formulated into the following standard form:

$$\mathbf{K} \cdot \mathbf{h}^e = \mathbf{f}^e \quad (16)$$

where

$$\begin{aligned} \mathbf{K} &= \sigma_{11} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial x} \frac{\partial \mathbf{R}}{\partial x} d\Omega + 2\sigma_{12} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial y} \frac{\partial \mathbf{R}}{\partial x} d\Omega + \sigma_{22} \int_{\Omega_e} \frac{\partial \mathbf{R}}{\partial y} \frac{\partial \mathbf{R}}{\partial y} d\Omega \\ \mathbf{f}^e &= -P_z \int_{\Omega_e} \mathbf{R} \sqrt{1 + \left[\left(\frac{\partial \mathbf{R}}{\partial x} \cdot \mathbf{h}^e \right)^2 + \left(\frac{\partial \mathbf{R}}{\partial y} \cdot \mathbf{h}^e \right)^2 \right]} d\Omega \end{aligned}$$

¹⁵² \mathbf{K} is the stiffness matrix, \mathbf{h}^e is the vector of unknown heights of control points in the elementary
¹⁵³ patch Ω_e , and \mathbf{f}^e is the right-hand-side force.

¹⁵⁴ 3.3. Iterative solution via Newton's method

In Eq. 16, the force vector \mathbf{f}^e changes with the height vector \mathbf{h}^e , which makes the equation nonlinear. We use Newton's method to solve the equation. According to Newton's method, the unbalanced force is defined as

$$\mathbf{F} = \mathbf{K} \cdot \mathbf{h}^e - \mathbf{f}^e \quad (17)$$

Then Eq. 16 is equivalent to $\mathbf{F} = \mathbf{0}$, which is solved through the iteration formulated as

$$\left(\frac{\partial \mathbf{F}}{\partial \mathbf{h}^e} \right)^{(\ell)} \cdot (\mathbf{h}^{e(\ell+1)} - \mathbf{h}^{e(\ell)}) = -\mathbf{F}(\mathbf{h}^{e(\ell)}) \quad (18)$$

where ℓ is the iteration number, and $()^\ell$ represents the value in the ℓ^{th} iteration. The derivative of \mathbf{F} with respect to the height vector is

$$\frac{\partial \mathbf{F}}{\partial \mathbf{h}^e} = \mathbf{K} - P_z \int_{\Omega_e} \left(1 + \left[\left(\frac{\partial \mathbf{R}}{\partial x} \cdot \mathbf{h}^e \right)^2 + \left(\frac{\partial \mathbf{R}}{\partial y} \cdot \mathbf{h}^e \right)^2 \right] \right)^{-\frac{1}{2}} \mathbf{R} \left(\left(\frac{\partial \mathbf{R}}{\partial x} \cdot \mathbf{h}^e \right) \frac{\partial \mathbf{R}}{\partial x} + \left(\frac{\partial \mathbf{R}}{\partial y} \cdot \mathbf{h}^e \right) \frac{\partial \mathbf{R}}{\partial y} \right) d\Omega. \quad (19)$$

155 The initial solution $\mathbf{h}^{(0)}$ is set as the planar footprint of the model. The stop condition is that the
 156 module of the unbalanced force \mathbf{F} is smaller than a threshold value, which is generally set as 10^{-12}
 157 within the present paper.

158 In the formulation, the distributed body force (e.g. gravity) is already considered. Additional
 159 concentrated and distributed forces in the vertical direction can also be easily applied. Assume
 160 that a concentrated force P is applied on the surface and is located to the point of patch Ω_e with
 161 parametric coordinates (ξ_p, η_p) . The force P is then distributed to the control points of the patch,
 162 by adding $\int_{\Omega_e} R(\xi_p, \eta_p) P d\Omega$ to the right-hand-side of Eq. 16.

163 4. Results

164 Without loss of generality, the footprints of the models are constrained in a simple square
 165 domain with the scale as $[-1, 1] \times [-1, 1]$. The loads are set as unit. Note that the dimensionless
 166 form of equilibrium function does not limit the generality of the present design algorithm.

167 4.1. Validation with the analytic catenary surface

A catenary is the curve that an idealized hanging chain assumes under its own weight if it is supported only at its ends. A catenary surface is the sweep surface of a catenary curve along a line perpendicular to the curve's plane. This surface is useful in the design of cathedrals and in Gothic arches used in Gothic architecture, to assure that no bending force is generated in the structure. Without loss of generality, for the catenary surface aligned with coordinate axes, the normal resultant stresses take uniform values and the shear resultant stresses vanish. Therefore, its self-supporting equilibrium equation is

$$-\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) = \sqrt{1 + h_{,x}^2 + h_{,y}^2} \quad (20)$$

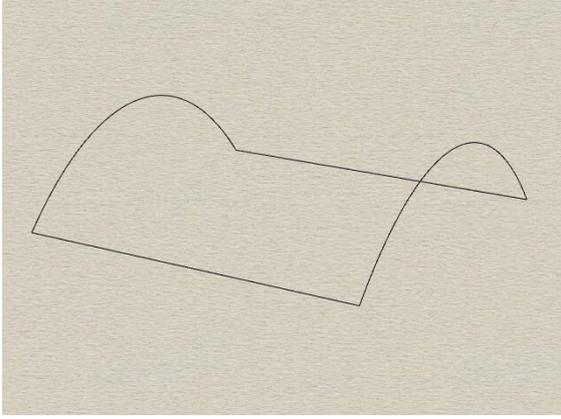
The analytic solution to this equation is the catenary surface

$$\bar{h} = -\cosh(x) + c \quad (21)$$

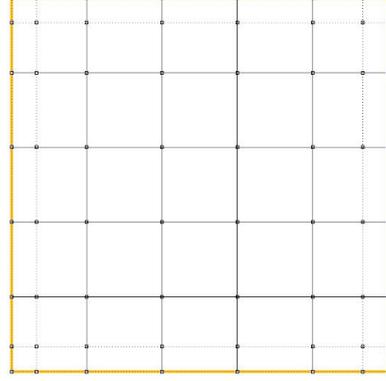
where c is an arbitrary constant. For example, setting $c = \cosh(2)$, we have

$$\bar{h} = -\cosh(x) + \cosh(2) \quad (22)$$

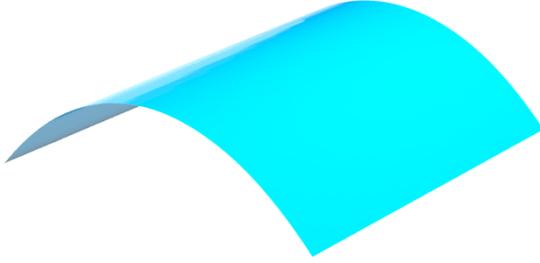
Fig. 5d illustrates the corresponding catenary surface. To validate our method, we compute the surface numerically using our proposed framework. The input coefficients are set according to Eq. 20 as $\sigma_{11} = -1$, $\sigma_{22} = -1$, and $\sigma_{12} = 0$. The corresponding Airy function is $\Phi = -\frac{1}{2}x^2 - \frac{1}{2}y^2$. The boundary curves of the catenary surface are set according to Eq. 22 and fixed as Dirichlet boundary conditions, as shown in Fig. 5a. The footprint on the horizontal plane forms a simple square over domain (x, y) , $x = (-1, 1)$, $y = (-1, 1)$, that is used as the initial solution for Newton's iteration (Sec. 3.3). Fig. 5c shows the shape obtained, which is almost the same as the analytic result as the ground truth. To measure the distance between the numerical result and the analytic



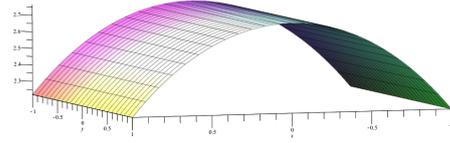
(a) Boundary curves



(b) Footprint domain



(c) Designed Result



(d) Analytical solution

Figure 5: The validation of our solver for the catenary model. (a) The boundary curves are specified according to concept of catenary surface (b) The square NURBS patch of the footprint is used as the initial surface of the Newton iteration (c) The designed result (d) The analytical solution as ground truth for comparison.

surface, the L_2 error is computed:

$$E_{L_2} = \sqrt{\int_{\Omega} (h - \bar{h})^2 d\Omega} = \sqrt{\sum_{i=1}^{1000 \times 1000} (h_i - \bar{h}_i)^2} \quad (23)$$

168 In the error computation, 1000×1000 evaluation points are evenly distributed over the horizon-
 169 tal footprint, h_i and \bar{h}_i are the calculated and the analytic heights respectively. We tested with
 170 increased polynomial degrees for NURBS (p -refinement) and refined spline with more control
 171 points (h -refinement), and show the errors in Table 1. The convergence rate is further visualized in
 172 Fig. 6: for each model described by splines with degree p , the convergence rate of the L_2 error with
 173 respect to the step size (distance between two neighboring control points) is $p + 1$. Our method
 174 can obtain a surface with L_2 error 9.48×10^{-4} in 5.07×10^{-3} seconds.

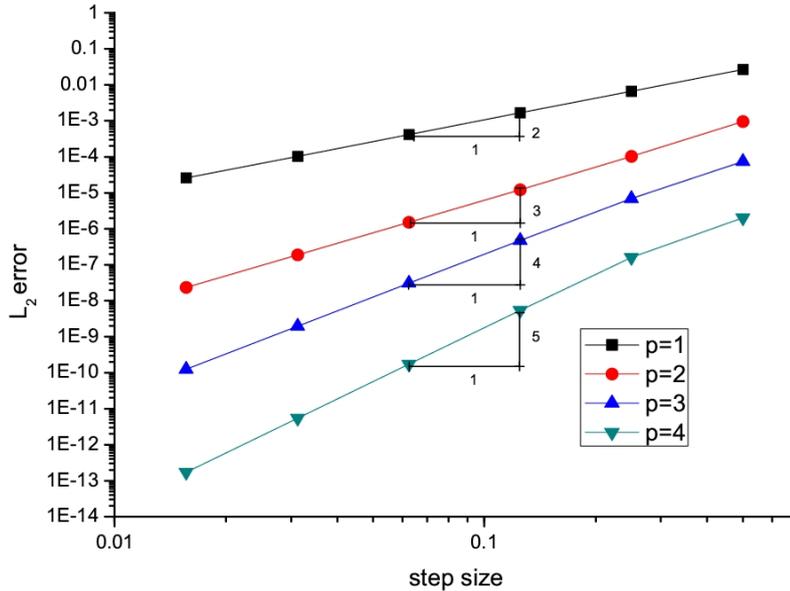


Figure 6: Convergence results for the catenary model. The x coordinate represents the step size and the y coordinate represents the L_2 error, which are shown in logarithmic form in base 10. Empirically, for each model described by splines with degree p , the order of convergence is $p + 1$.

175 4.2. “Tent”

176 The tent model is inspired by vault roofs as shown in Reference [15]. Starting from an initial
 177 conceptual sketch of the shape, our algorithm turns it into a self-supporting surface. The boundary
 178 of the footprint is first drawn with CAD tools and then the design domain is modeled by NURBS
 179 patches. The layout of patches is shown in Fig. 4b. The self-supporting tent surface is designed
 180 by setting the stresses as $\sigma_{11} = 1$, $\sigma_{22} = 0.8$, and $\sigma_{12} = 0$, and is shown in Fig. 7.

181 4.3. “Crest”

182 The original “Crest” (Fig. 3) is an experimental sculpture designed by Zaha Hadid Architects.
 183 To construct it, the designers assembled very thin aluminium panels together into a flat plate and
 184 then lifted the plate into a self-supporting structure. The designers of “Crest” intend to investigate
 185 “the relationship between formal arrangement and structural performance”¹, a topic with which
 186 we have affinity in this work. Inspired by the sculpture, using our algorithm, we create variations
 187 of self-supporting Crest models with different inner stress states. There is the pattern that the
 188 height of the surface increases when the ratio of stresses σ_{22}/σ_{11} decreases. This pattern may help
 189 the architects to predict what shapes they will obtain, thus providing them a useful tool to explore
 190 possible designs. Fig. 8 shows three results for the Crest concept. The designers can choose the
 191 optimal design among them (and many others) according to their own aesthetics taste.

¹According to the description in <http://www.zaha-hadid.com/architecture/crest-installation/>

Table 1: Convergence tests of the catenary problem. The tolerance of the Newton iteration is 10^{-12} .

Degree	Refine times	Cp per-side	L_2 error	Computation time(seconds)
1	1	5	2.678E-02	2.150E-3
1	2	9	6.661E-03	7.505E-3
1	3	17	1.659E-03	3.687E-2
1	4	33	4.142E-04	2.541E-1
1	5	65	1.034E-04	2.753E+0
1	6	129	2.587E-05	6.146E+1
2	1	7	9.479E-04	5.070E-3
2	2	11	1.022E-04	1.958E-2
2	3	19	1.220E-05	9.809E-2
2	4	35	1.505E-06	6.351E-1
2	5	67	1.875E-07	5.461E+0
2	6	131	2.342E-08	1.935E+2
3	1	9	7.430E-05	1.126E-2
3	2	13	6.916E-06	4.751E-2
3	3	21	4.784E-07	2.527E-1
3	4	37	3.105E-08	1.854E+0
3	5	69	1.975E-09	3.106E+1
3	6	133	1.245E-10	5.457E+2
4	1	11	2.040E-06	2.578E-2
4	2	15	1.606E-07	1.113E-1
4	3	23	5.405E-09	5.243E-1
4	4	39	1.724E-10	3.641E+0
4	5	71	5.436E-12	1.038E+2
4	6	135	1.706E-13	1.569E+3

192 *4.4. Top of Lilium tower: comparison with TNA*

193 The top of Lilium Tower is used for comparison with the TNA methods. Lilium tower is a
194 building in Warsaw, Poland, also designed by Zaha Hadid Architects. In [9] a self-supporting
195 mesh defined by 1201 vertices and 3504 edges approximating the top of Lilium tower is given.
196 With our NURBS-based representation, only 36 control points are used, as shown in Fig. 9a. So
197 compared with the TNA-based method using a discrete mesh surface, the shape computed by our
198 method is smooth and the variables needed to describe the geometry are much fewer. As a result,
199 our algorithm has better computational efficiency, as further discussed in section 5.1. In Masaaki et
200 al.’s work [15], which also uses parametric surfaces for representing self-supporting surfaces, dis-
201 crete self-supporting conditions, however, are still based on the equilibrium of the thrust network,
202 which lacks the high order precision achieved with few variables that our isogeometric model
203 provides.

204 *4.5. Trihole and Stadium*

205 The “Trihole” and “Stadium” models have complex topology. Our method handles them with-
206 out difficulty. The input footprints are specified according to the top views of the mesh models

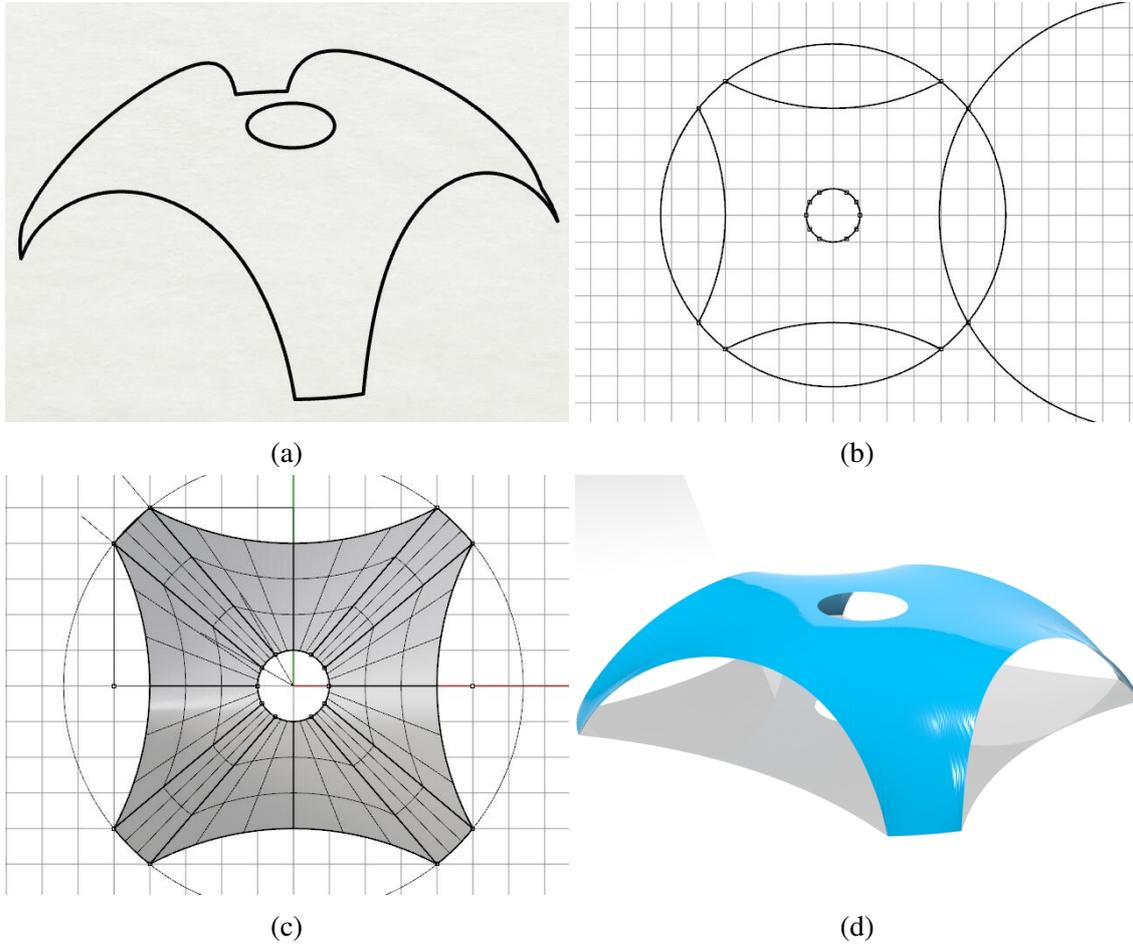


Figure 7: The design process of the tent model. (a) The design concept. (b) The input model is designed with CAD software. (c) The input model described by NURBS patches. (d) The output masonry structure.

207 shown in [8] and [9]; parts of the boundaries are fixed to the ground. Fig. 10 illustrates the com-
 208 puted self-supporting surfaces with our method.

209 5. Discussions

210 5.1. Comparisons with TNA and IGA based methods

211 We model masonry surfaces by parametric NURBS, which is suitable for describing smooth
 212 geometry. Compared with TNA-based methods, which use discrete graphs and meshes, the para-
 213 metric description defines smooth surfaces with a smaller number of control points, thus enjoying
 214 a considerable advantage in computational efficiency. The runtime statistics of our algorithm are
 215 listed in Table 2. All the experiments are done on an Intel i7 processor clocked at 2.7GHz. For
 216 example, the catenary and the crest models are defined with a single patch, thus the number of con-
 217 trol points used to define the geometry is very small while the smooth shapes are well represented.
 218 Our algorithm finds the self-supporting shapes from the initial planar configurations within less
 219 than 0.1 seconds for both models. Complicated models with holes are represented using multiple

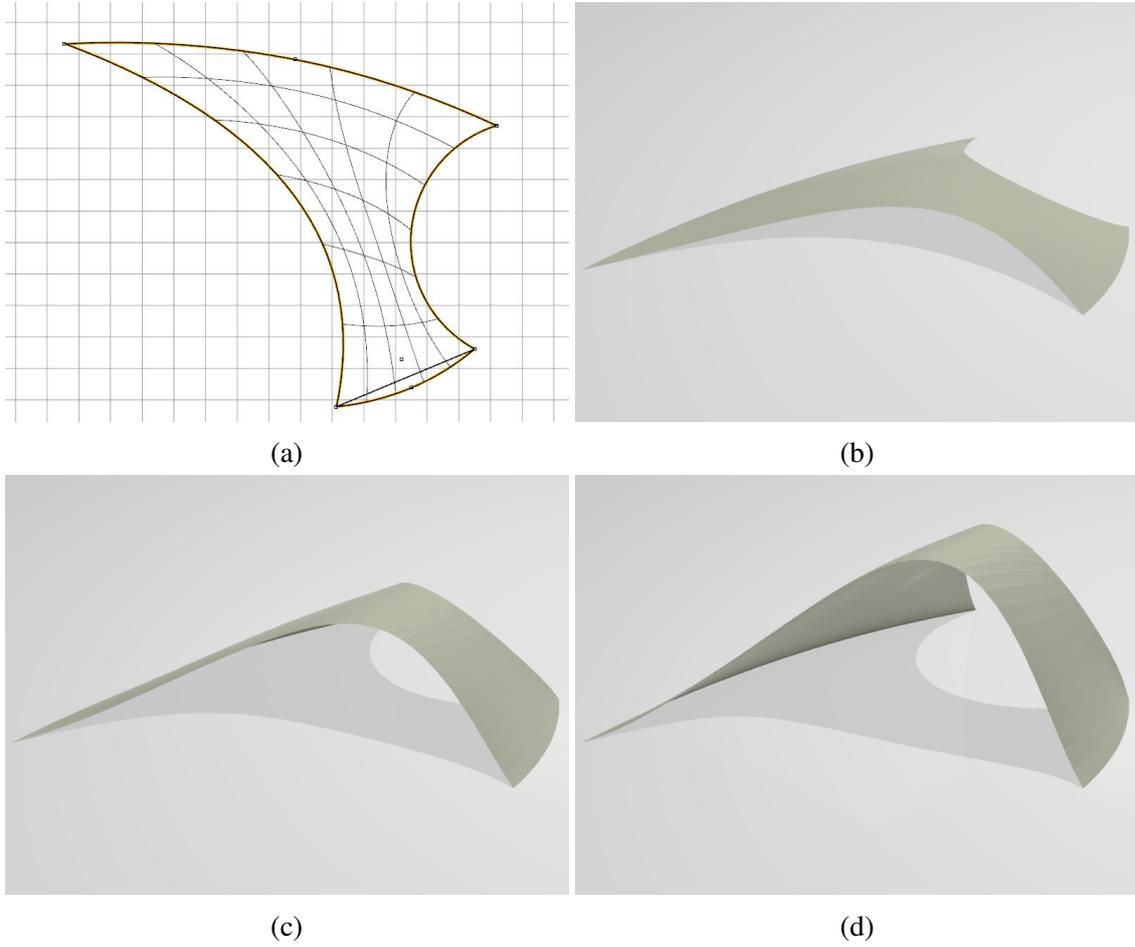


Figure 8: Crest model. (a) Free form curves and patch inspired by the “Crest” sculpture. The stresses are set as follows: $\sigma_{11} = -1$, $\sigma_{12} = 0$ are used for all the examples. The other stresses are (b) $\sigma_{22} = -0.6$, (c) $\sigma_{22} = -0.3$, (d) $\sigma_{22} = -0.2$.

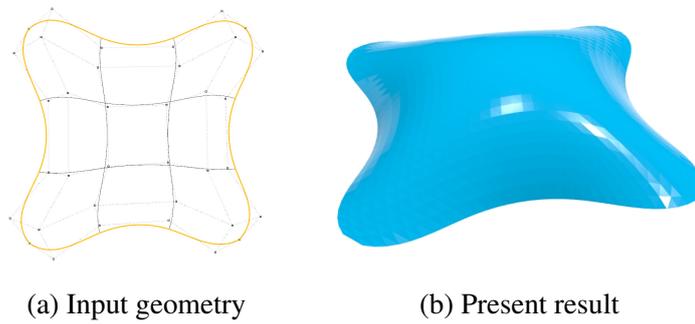


Figure 9: Lilium tower. (a) The input geometry; (b) Result obtained by present algorithm with stresses as $\sigma_{11} = -0.5$, $\sigma_{22} = -0.5$, and $\sigma_{12} = 0$. It is a continuous smooth surface described by NURBS, and the triangulation shown in the figure is only created by the rendering.

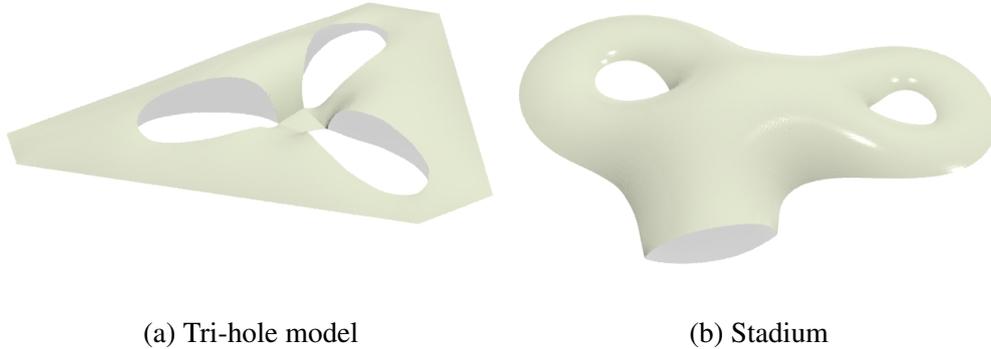


Figure 10: Two complex self-supporting surfaces computed by our method. (a) The tri-hole model has stresses as $\sigma_{11} = -0.2$, $\sigma_{22} = -1.0$, and $\sigma_{12} = 0$. (b) The stadium model has stresses as $\sigma_{11} = -0.3$, $\sigma_{22} = -0.3$, and $\sigma_{12} = 0$.

220 NURBS surface patches, as in the examples of the tent, the top of liliun tower, and the tri-hole
 221 models. Adjacent patches share the control points along their common boundary, so that the sur-
 222 face has C^0 continuity. Again our algorithm can effectively find the self-supporting shapes, with
 223 computation time only about 25% of that by TNA in [9].

Table 2: Computational statistics of our algorithm.

Fig.	Con. Pts.	Iters.	Err.	Time (s)
5c	25	12	10^{-12}	0.027
7	828	4	10^{-12}	2.069
8	56	4	10^{-12}	0.093
9b	36	4	10^{-12}	0.044
10b	1158	4	10^{-12}	4.218

Table 3: Comparison of computational efficiency. The termination condition is that the tolerance of the Newton iteration is 10^{-12} . For a simple shape that can be described by a single patch, our method can obtain a self-supporting shape in real time (less than 0.1 seconds). For whole shapes which must be described by multi-patch geometry, the present algorithm only needs about 25% time of that when using TNA.

Fig.	Our algorithm			Ref. [9]		
	Con. Pts.	Iters	Time (s)	Vertices	iterations	Time (s)
9b	36	4	0.044	1201	9	21.6
10b	1158	4	4.218	1535	21	17.0

224 Alic and Persson’s dynamic relaxation method [30] and Philipp et al.’s updated reference strat-
 225 egy [28] also use isogeometric analysis for the computation of membrane structures. In these two
 226 papers the form-finding approach is used to compute architectural surfaces. Our method is more
 227 practical and effective for the design of masonry shapes. In particular, one advantage is that our
 228 algorithm does not need a specific input shape as the target, and useful self-supporting shapes

229 can be obtained efficiently by tuning the inner stress states. The form finding methods follow
230 the reverse design approach: an existing model must be used as the input and the outputs are all
231 in similar shapes with the input. Another advantage is the computational efficiency: our method
232 applies Newton’s method to handle the nonlinear loads and converges within very few (typically
233 about 5) iterations. The results in Table 3 show that form finding methods generally take more
234 computation time.

235 5.2. Influence of Airy stress

236 In this section, we explore the influence of Airy stress in tuning the self-supporting shape. To
237 carry out the analysis, we use a simple square domain of $[-1, 1] \times [-1, 1]$ on which self-supporting
238 surfaces are defined.

239 5.2.1. Scale and ratio

240 In actual masonry buildings, gravity loads vary from dozens to thousands of pascals depending
241 on the building material, while geometric scales range from meters to dozens of meters. According
242 to the control formula in Eq. 10, the relative ratio of Airy stress to the gravity load determines
243 the shape. Therefore, without loss of generality we assume a unit gravity load, and fix all four
244 boundaries of the surface to the ground. We explore the effect of uniform Airy stress functions
245 which have zero shear stress ($\sigma_{12} = \sigma_{21} = 0$) and varying normal stresses σ_{11}, σ_{22} . In addition,
246 we always set $\sigma_{11} > \sigma_{22}$, because models with $\sigma_{11} < \sigma_{22}$ can be obtained simply by rotation. Our
247 results show that the feasible design domain of Airy stresses under this setting locates within a
248 triangle, as plotted in Fig. 11. The main conclusions from the test are as follows. Through this
249 example, it is shown that the meaningful values for the Airy stresses reside in a well-defined region
250 and the obtained shapes are predictable by tuning the values.

- 251 a) When both stresses are tiny, which means the structure is in a loose state and there is not
252 enough compression force to hold the pieces together, Newton’s iteration will not converge
253 and no self-supporting shapes can be obtained.
- 254 b) When stress increases, the height of the obtained shape generally decreases. This phenomenon
255 is explained by the fact that equilibrium with smaller plane stresses can be obtained with steeper
256 shapes, until reaching the extreme case when walls are built straight up with blocks. In the
257 opposite direction, when inner stress increases, the height of the obtained shape decreases,
258 until it becomes planar in the extreme situation.
- 259 c) When the ratio of two normal stresses σ_{11}, σ_{22} increases, the shape cross sections in the two
260 directions will be more different, as shown in Fig. 12.
- 261 d) The feasible design domain in this problem is located within a triangle with vertexes $(0.3, 0.3)$,
262 $(1.49, 1.49)$ and $(3.2, 0.002)$. A symmetrical triangle plotted by the dashed line is the feasible
263 domain for $\sigma_{11} < \sigma_{22}$.

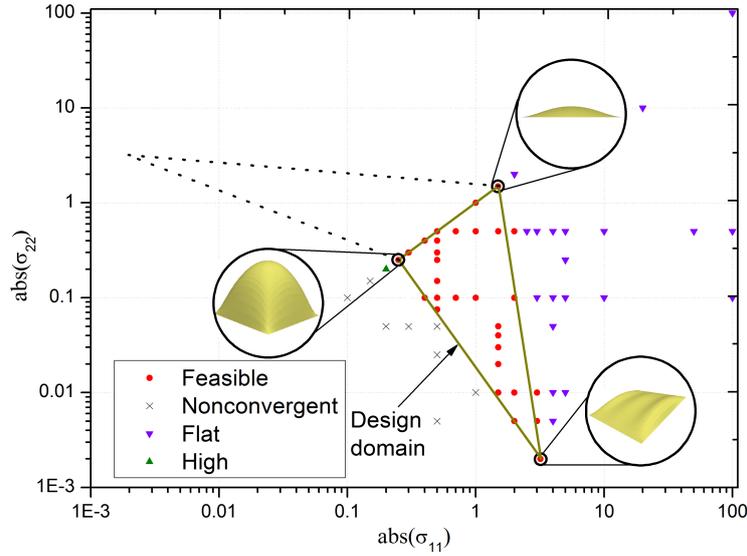


Figure 11: The feasible design domain of Airy stresses. Shear stresses are set to zero, and the absolute value of normal stresses are plotted in logarithmic-logarithmic coordinates. The red circular spots represent feasible values for obtaining self-supporting shapes. The cross spots mean that the Newton iteration does not converge. The inverted triangles represent flat shapes that are not interesting, while the triangles represent clifty shapes. The values are chosen by practical experiences that shapes with a maximum height less than 0.2 are deemed flat, and more than 4 as high.

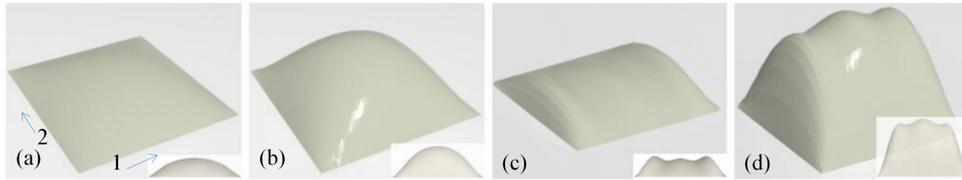


Figure 12: The influence of the scale of Airy stress functions on self-supporting shapes. The insets on down-right corners show the side views of the shapes. For all models $\sigma_{12} = \sigma_{21} = 0$. (a) $\sigma_{11} = \sigma_{22} = -1$, (b) $\sigma_{11} = \sigma_{22} = -0.5$, (c) $\sigma_{11} = -2, \sigma_{22} = -0.01$, (d) $\sigma_{11} = -0.5, \sigma_{22} = -0.1$.

264 5.2.2. Propagation of boundary conditions

265 In this section, a square domain with two opposite and curved boundaries is used to study the
 266 influence of boundary conditions. A model with four patches is used. The boundary curve is given
 267 by the function $0.3 |\sin(\pi x)|$, as shown in Fig. 13. The L_2 projection method is used to force the
 268 boundary of the model to keep the same shape as the boundary curve.

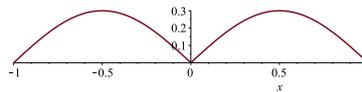


Figure 13: The boundary curve.

269 First, a sequence of different stresses with zero shear force and corresponding results are shown
 270 in Fig. 14. We see that when the normal stress σ_{22} is small, the influence of the curved boundary

271 is limited to the sides and the interior domain is not affected; with the increase of σ_{22} , however,
 272 the influence propagates and can even dominate the whole shape.

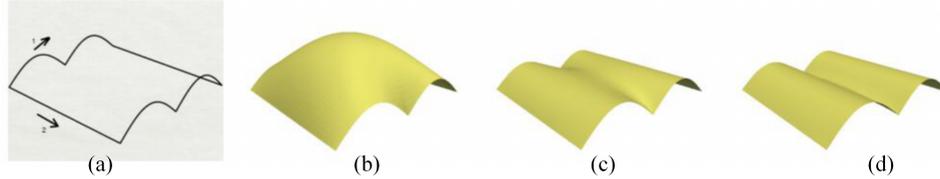


Figure 14: Influence of the boundary increases with the corresponding Airy stress values. Curved boundary conditions shown in Fig. 13 are applied on two opposite sides of the square. The other two sides are pinched, with a constant normal stress $\sigma_{11} = -0.5$. The absolute value of normal stresses on the wiggly sides σ_{22} gradually increase. (a) the input boundaries, (b) $\sigma_{22} = -0.5$, (c) $\sigma_{22} = -5$, (d) $\sigma_{22} = -50$. Shape construction in (d) is difficult, because the inner stress is large and huge force must be applied on the boundary to maintain the stress state, which is not practical in construction.

To investigate the propagation direction of the boundary conditions under the influence of stress functions, we further conduct the following tests. According to theory of elasticity, the two main stresses within a membrane can be computed as follows:

$$\left. \begin{matrix} \sigma^1 \\ \sigma^2 \end{matrix} \right\} = \frac{\sigma_{11} + \sigma_{22}}{2} \pm \sqrt{\left(\frac{\sigma_{11} - \sigma_{22}}{2}\right)^2 + \sigma_{12}^2} \quad (24)$$

The two main stresses are both negative; the one with the larger absolute value is denoted as σ^1 . The angle between the main stress σ^1 and the x coordinate axis is denoted as α^1 , and

$$\tan(\alpha^1) = \frac{\sigma^1 - \sigma_{11}}{\sigma_{12}}.$$

273 Five stress states are picked from Mohr's stress circle with main stresses $\sigma^1 = -50$, $\sigma^2 = -0.5$.
 274 The angles α^1 of the five states are 90° , 60° , 45° , 30° and 0° . In Fig. 15, the top view of the
 275 obtained shapes are plotted so that the propagation of curved boundary condition can be clearly
 276 observed. The results show that the propagation direction of boundary conditions coincides with
 277 the direction of main stress. This result is very useful for improving our understanding about the
 278 behavior of masonry surfaces.

279 5.3. Influence of parameterizations

280 The influence of parameterization for multi-patch models is tested. Fig. 16 shows two para-
 281 metric models for an input shape with the same planar boundary: the left model has four patches,
 282 while the right model has three patches. The outer boundaries of the models are fixed to the ground
 283 and the central circular boundary rises to form self-supporting surfaces. The Airy stress is set as
 284 $\sigma_{11} = \sigma_{22} = -0.4$, $\sigma_{12} = 0$. The results show that differences in the parametric models do not
 285 significantly affect the final shapes obtained using our algorithm. The computed masonry shapes
 286 from these two parameterizations are almost the same, with their Hausdorff distance being 0.68%
 287 of the bounding box diagonal length of the result shapes.

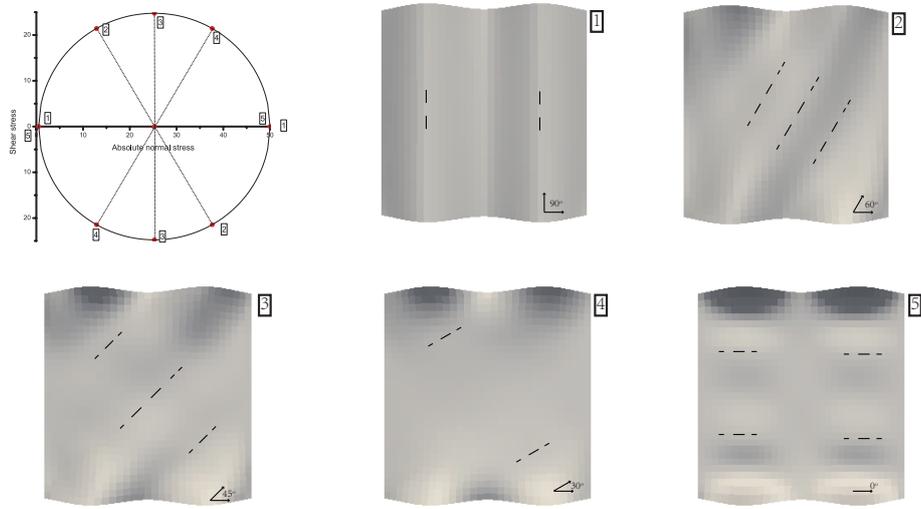


Figure 15: Self-supporting shapes corresponding to the five stress states picked from the Mohr's stress circle. The main stress direction coincides with the propagation direction of applied boundary conditions.

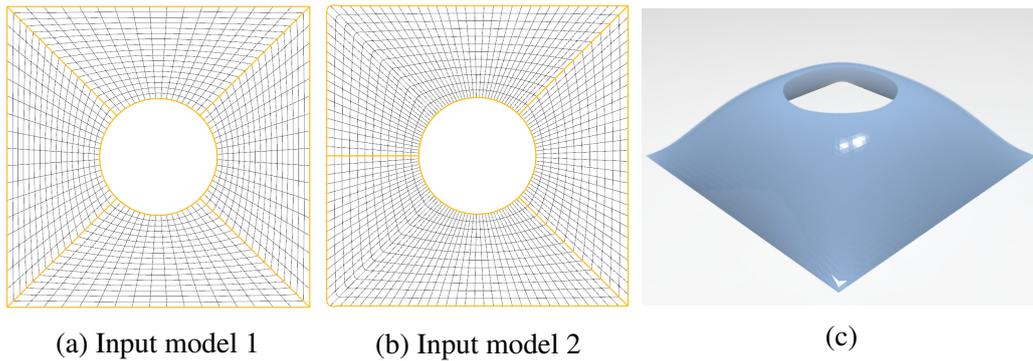


Figure 16: Two different parametric methods for the “plate-hole” model with the same geometrical shape. Our algorithm obtains stable results for these two parametric models. (a) Input model with four patches; (b) Input model with three patches; (c) The obtained shapes are close to one another and cannot be visually distinguished.

288 5.4. Exponential Airy stress

Constant stress states have been used in previous examples so far. However, Airy stress functions are not restricted to constant stress states. In this section we show an example with varying stress states. In particular, exponential functions make a qualified candidate for Airy stress function because of their strict convexity. For example, the function

$$\Phi = -(e^x + e^y) \tag{25}$$

is concave and thus the self-supporting condition is always satisfied. In this case, the stress tensor takes the form

$$\sigma = \begin{bmatrix} -e^x & 0 \\ 0 & -e^y \end{bmatrix}.$$

21

289 The shape of the Airy stress function is shown in Fig. 17(a). The self-supporting shape is shown
290 together with the corresponding Airy stress in Fig. 17(b), and in different views in Fig. 17(c) and
291 17(d). This example demonstrates the ability of our algorithm to deal with various types of Airy
stress functions.

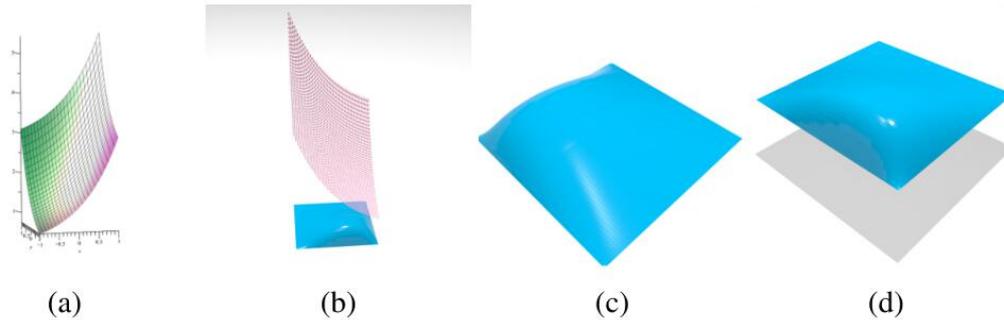


Figure 17: Computational results obtained for an exponential Airy stress. (a) Absolute value of the Airy function. (b) Obtained shape and corresponding Airy function. (c) and (d) show the shape in different perspectives.

292

293 6. Conclusion

294 In this paper, self-supporting masonry surfaces are modeled with NURBS based IGA and
295 a heuristic strategy for designing the surfaces is proposed. The equilibrium equation for self-
296 supporting surfaces is derived from membrane shell theory and can be effectively solved by the
297 IGA representation. Nonlinear equations that consider changing gravity loads with shapes are
298 solved via Newton's method. The convergence rate of the presented algorithm is shown to be
299 one order higher than the degree of applied NURBS basis functions. Airy stress states within the
300 shape can be manipulated and the corresponding self-supporting surfaces are efficiently calculated.
301 Moreover, the Airy stress space for meaningful designs is explored and discussed, which provides
302 guidance for design. Various self-supporting structures with complex topology and shapes are
303 demonstrated. These shapes can help architects to find the ideal conceptual design, and to get an
304 idea of the stress states within the design. Overall, the proposed algorithm accurately and effi-
305 ciently calculates the shapes of self-supporting surfaces and provides an effective tool for design.

306 There are some limitations of the present method. The stress state of masonry structure is
307 wider than that described by Airy stress function, because divergence free stress tensors exist that
308 are not second-order differentials of a function. In future works, the algorithm to solve the general
309 differential equation of self-supporting masonry using isogeometric analysis, without the aid of
310 Airy stress function can be investigated. The present algorithm focuses on the elastic deformation
311 and the plastic deformation can be embedded into the present strategy in the future work for the
312 evaluation of existing masonry structures. Higher continuity such as C^1 smoothness along the
313 boundary of the adjacent patches of complex structure can also be considered.

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