Material driven design for a chocolate pavilion

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HIGHLIGHTS

- Determination of structural properties of compound chocolate.
- Physical exploration of material appropriate structural systems for chocolate.
- Parametrically integrated design-to-construction process for free-form chocolate shell structures.
- Integration of material specific structural, manufacturing, and construction constraints into the design process.

ARTICLE INFO

ABSTRACT

This paper presents a study of chocolate's structurally unusual material properties and a parametric design-to-construction approach for an architectural chocolate pavilion. Chocolate's rheological properties suggested exploration of four structural typologies: a pneumatic form, an inverted branching form, a saddle form, and an inverted hanging cloth form. Material tests revealed a compressive strength/weight ratio 24 times smaller than standard concrete. To use unreinforced chocolate, this restriction dictated a form with minimal bending: an inverted hanging shell with voids. An integrated form-finding, void-optimization and mold layout process was employed to minimize self-weight. Pre-casting planar pieces allowed for best control of material quality but added further design constraints. Prototypes demonstrated how the parametric workflow allows design exploration driven by adjustable material constraints, further integrating design and construction into an interdependent process.

1. Introduction

Given the challenge to explore chocolate's structural capabilities, the design of architectural shell structures made from compound chocolate is investigated. When first introduced to the idea of using chocolate as a building material, one might jump to the imagery of Charlie and the Chocolate Factory. Just like the appeal of Willy Wonka's factory lies in the technological complexity of his extraordinary uses for chocolate, the challenge of this project is to utilize novel design practices to create a structural system that allows chocolate to be seen from a new perspective as an experimental building material. Chocolate is often used for artistic purposes, but using chocolate as a structural material and not just as a sculptural medium poses significant challenges. Its relative structural weakness and unique rheological properties require a system of design specifically tailored to the material itself. To achieve this, a parametric design process is used for the design and construction of a force-modeled long span structure from this unorthodox building material.

In this paper, we describe the development of the design process for chocolate shells. Since chocolate has not been analyzed as a structural material before, Section 2 describes the determination of the chocolate formula best suited for this purpose and what engineering properties can be expected from it. Section 2 also includes the process of physical experimentation with chocolate. These experiments explore the possible formal expressions that relate to the physical processes of pouring, dipping and coating and their physical form finding potential for chocolate. The parametric design-to-construction workflow that enables integrated form-finding, structural analysis and optimization, design exploration, and production of manufacturing layouts is presented in Section 3. Section 4 reports on the small-scale mock-up that sheds light on the viability of the digital workflow. Section 5 discusses the design and construction process of the full-scale structure designed for a

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café exhibit, and Section 6 concludes with how and why the digital design and construction process must be inseparably connected to the chocolate properties and how this process allows for an exploration of expressive forms by the designer. Overall we present this paper to develop awareness for material specific computational workflows and approaches on how to integrate from finding principles into the steering of structural form.

2. Physical form finding driven by material structural behavior

2.1. Chocolate material properties

The first step in a material driven design process is to understand the material properties that need to be designed for. The word "chocolate" encompasses a wide range of mixtures that contain elements from the cocoa bean. For a product to be legally considered "chocolate" in the United States, it must go through the processes of blending and conching, and contain a minimum amount of cocoa and cocoa butter as its only fat source. This form of chocolate is expensive, melts at temperatures near room temperature, and can become unstable very quickly. For use in structural applications, these properties can all be improved by changing the product's formula to create a "compound chocolate". Many commercially available chocolate products and chocolate-covered baked goods use compound chocolate, not strict "chocolate". The major difference between the two is that the fat used for compound chocolate does not need to be cocoa butter; it can be other types of vegetable fat. This change in ingredients as well as differences in manufacturing means that the material can be melted and cast many times without degradation. Throughout this paper the word "chocolate" is used to refer to the "compound chocolate" used as the primary material in the investigation. Food scientists have intensively studied and optimized chocolate to control properties such as taste, texture, appearance, rheology, production and shelf life [1]. However, no studies have been carried out to identify structural material properties such as strength and elasticity. This effort is quite complex, since the effects of changing the formula or manufacturing procedure on chocolate's structural behavior are unknown.

The first tests compared two formulations of chocolate, whose ingredients are shown in Table 1. Hydrogenated palm kernel fat was chosen because of its high melting point, nearly 43 °C—given the label HMP. The second formula replaced one third of the fat with a lower melting point variant, given the label LMP. To establish the strength and Young's modulus of these two formulas, standard uniaxial compression (see Fig. 1) and tensile split cylinder tests were used. To create the test specimens, the chocolate was melted at 52 °C, cast into standard 3" diameter concrete cylinder molds preheated to the same temperature as the chocolate, and set at 4 °C. HMP was stronger and stiffer than LMP, while also being more consistent in casting and easier to handle. Based on the encouraging results of HMP, four additional formulas were developed. Milk permeate was replaced with Inulin, a type of dietary fiber, and the fat content and particle size were varied. The particle size was controlled by refining the dry ingredients before liquefying the chocolate. The four variants were Low-Fat Refined, Regular-Fat Unrefined, Low-fat Unrefined and Regular-fat Granulated, which used granulated instead of powdered sugar. The variants were designed with the hypothesis that less fat and smaller particles, with greater surface area for cohesion, both make the chocolate stiffer. The same compression and tension tests performed on HMP and LMP were performed on these four variants.

An unintended consequence of lowering the fat content and having larger particle sizes was that the molten chocolate became more viscous and tended to entrap air during the setting process. Furthermore, the material's quick setting time made vibration less effective for removing entrapped air, and this air reduced

Table 1
Ingredients of two compound chocolate formulations.

Formula	Ingredients by (%)				
	Powdered sugar	Cocoa powder	Fat	Milk permeate	Soy lethicin
HMP	57.77	7.97	30.03	3.98	0.40
LMP	57.64	7.95	29.88	3.97	0.41

Table 2
Material properties of compound chosen as building material.

Chocolate formulation	HMP
Density	12.9 kN/m^3
Compressive yield stress	0.6 N/mm^2
Tension rupture stress	1.0 N/mm^2
Young's modulus	47,000 kN/m^2
Creep viscosity	2.66E11 Pa s

Table 3
Comparison of material properties with common engineering materials.

Material	Strength (N/mm^2)	Density (kN/m^3)	Young's modulus (kN/m^2)
Steel	413	76.98	199E6
Concrete	27	23.56	29E6
Chocolate	0.6	12.88	45E3

the strength of the material. The Young's modulus did not vary significantly between the variants. HMP remained the best choice, based on its having highest compressive yield stress (0.6 N/mm^2) and tensile rupture stress (1 N/mm^2) and its ease of manipulation. From an engineering perspective, the compressive and tensile load bearing capacities were within a small enough range for the material to be considered isotropic. Since the material was very close to its melting point at elevated room temperature, we hypothesized that creep would pose a material concern. For this purpose, we performed a three point bending relaxation test, which was used to estimate a material's creep viscosity [2]. The results of these tests revealed that chocolate creeps in a time-logarithmic manner, relatively quickly compared to other materials such as concrete or wood. A simplified creep calculation estimated that the material under modest compression would creep at 0.3% per day. Table 2 summarizes the relevant structural properties of the chosen formulation, HMP. Table 3 compares the properties of this formulation with the more common structural materials steel and concrete. These observations suggest the necessity of form-finding techniques to generate membrane/shell systems that will reduce the material stress and size optimization to bring the self-weight down.

2.2. Physical form finding

In order to find a suitable structural typology for chocolate, physical form finding experiments were employed. These experiments also allowed exploration of the less quantifiable properties that affected the potential designs. Experimentation based on chocolate's rheological properties, such as the viscosity's dependence on temperature, layering based on surface tension, and the visual quality of the surface changed how the material read aesthetically. Four different historic physical form finding techniques that lent themselves to this application were used for the fabrication of small models. These models were analyzed based on structural ability, ease of construction, and aesthetic expression. These small models were structurally valid for a structure on a larger scale because at both scales, the only load was self-weight. Other, possibly asymmetric, loads on a large structure, such as wind and snow, did not need to be considered, as the design would be exhibited in temperature controlled indoor environments.
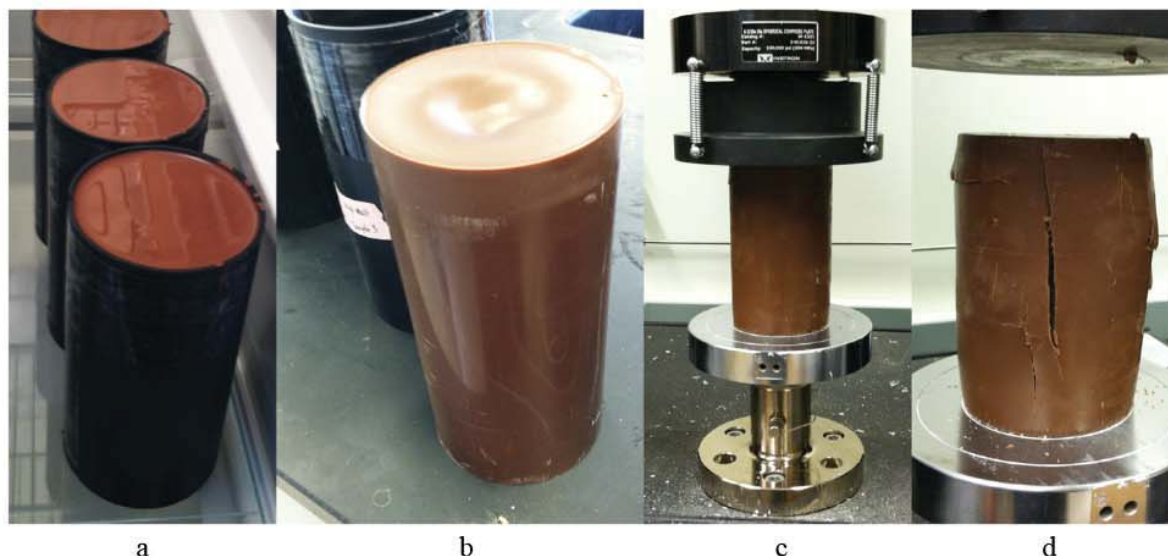
Fig. 1. Setting of the chocolate cylinder samples (a, b), and performance of uniaxial compression tests until failure (c, d).

2.2.1. Pneumatic form

The pneumatic form-finding technique presented itself as an obvious form-finding method that suited the 'pourable' characteristic of chocolate. In this method, a sealed flexible membrane is inflated with air to create a curved surface [3]. This surface is in pure tension under pressure. For a pneumatic form in chocolate, balloons were used as pneumatic formwork (Fig. 2(a)). Liquid chocolate was cast onto the membrane (Fig. 2(b)). Once hardened, the pressure was released and the shell made freestanding. This curved form is ideal for pressure loads, acting perpendicularly to the membrane surface, while gravity always acts downwards. When the normal of the surface deviates from the vertical, as is the case in non-shallow shells (see Fig. 2(c)), this difference in loading cannot be ignored. As a result, a larger scale shape could experience substantial undesirable bending stresses and limits the design possibilities.

The relatively low viscosity of melted chocolate compared to concrete creates a construction difficulty. Although successful on a small scale, the lack of shear resistance in liquid chocolate hinders control over the shell thickness at larger scales. Controlling flow rates at different scales would pose an additional challenge but also adds to the aesthetic reading of chocolate. Any overflow pooling on the work platform forms a base to anchor the shell and makes the pouring process visible (Fig. 2(d)). Finally, this on-site fabrication technique would require incremental pouring of the liquid material over the pneumatic form, which would complicate predicting its structural behavior. To create a monolithic structure at a larger scale, this casting technique would prove to be difficult to implement in a controlled manner.

2.2.2. Inverted branching form

Branching or "tree" systems efficiently transfer large surface loads to a single point and lend themselves to a canopy structure. If the geometry of the branching elements is correctly derived from the flow of forces, these elements act entirely in compression [4]. An inverted hanging thread model generates this form, as shown in Fig. 3(a). To create a branching form in chocolate, a series of strings were attached to a base surface, connected at non-sliding branching nodes, and pulled taut. The pinned support nodes at the base plate could rotate with three degrees of freedom and the branching nodes could rotate and displace with six degrees of freedom. By applying liquid chocolate to the strings the structure was set in place. Chocolate was applied in two ways: directly to the strings

while they are in place, and by submerging the strings in chocolate before being placed in the network. Sufficient chocolate flowed onto the base surface to form a connection between the support nodes, providing the capacity required to hold the nodes in place, avoid rotational disequilibrium and creating an aesthetic reading of chocolate flow. The branching form that evolved was a direct result of the chocolate flow, and, in theory, the inverted result was a compression only system (Fig. 3(b)).

From a structural point of view, this form-finding technique did not take into account the effect of the buckling instability of the slender branching elements. Upon inversion of the small scale prototype, the central support column suddenly failed by deflecting sideways at a compressive stress much lower than its yield stress. To increase the buckling capacity of the branching elements, the chocolate drenched strings would need a significantly larger diameter. This constraint was hard to fulfill, especially at a larger scale. Due to its relatively low viscosity, only a thin layer of chocolate was added each time the string was dipped or material was painted on. As shown in Fig. 3(c), at a larger experimental scale, the strings took on catenary shape and lacked cross sectional area to hold the structure up. This issue of buckling posed a challenge for building a structure of this type.

2.2.3. Saddle form on flexible framework

Casting onto a pre-stressed structural membrane with two opposing high and two opposing low points creates in a highly efficient shell. The resulting saddle shape is similar to a hyberbolic paraboloid (hypar), whose constructional and structural qualities have been extensively researched and exploited in design and construction of reinforced concrete shells [5]. The hypar form can be described using straight line generators and thus lends itself well to solid formwork composed of planar elements. Typically, molds require large amounts of material to make stiff forms supported on rigid scaffolding. The use of flexible pre-stressed formwork, properly anchored, substantially reduces the amount of mold material and can allow for tighter control over the form, resulting in improved shell behavior and efficiency [6]. The global structural behavior of the saddle shell formed on flexible formwork can be understood as follows: the self-weight of the chocolate causes the arching action between the two lower supports. This action is opposed by the hanging action of the shell between the high points which is aided by the cantilevering balancing action of the two resulting canopies (Fig. 4(a)).
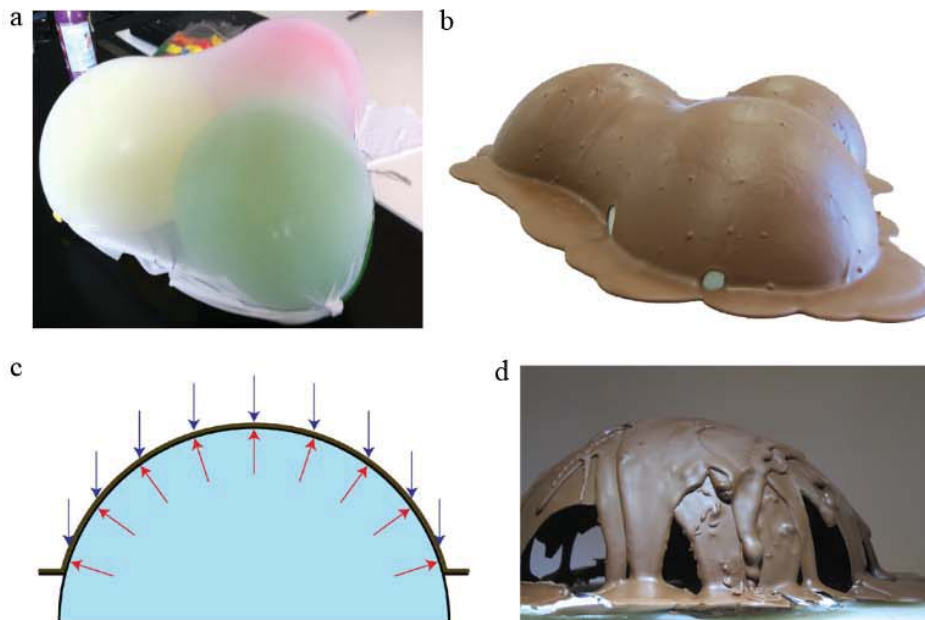
Fig. 2. Pneumatic formwork (a) upon which freestanding chocolate shell (b) is poured. Pressure (red) and gravity (blue) loads act on a pneumatic shape (c). Varying the rate and timing of chocolate application provides a visible "poured" effect (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
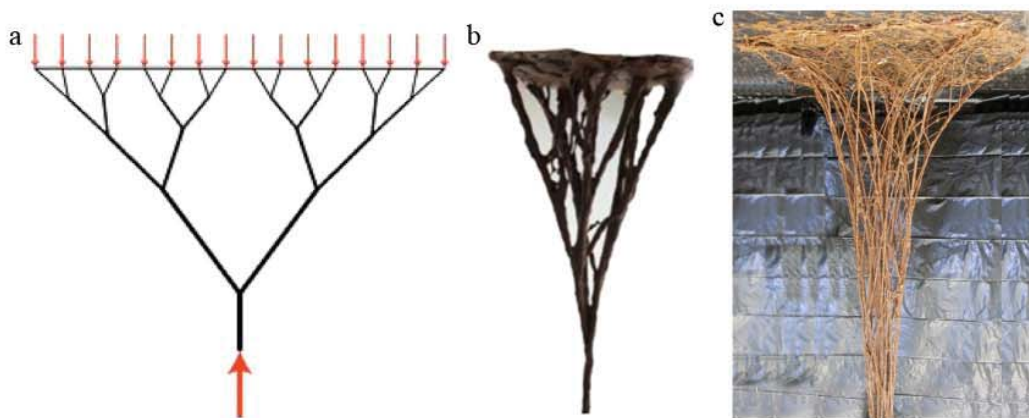

Fig. 3. A branching system composed of taut strings creates an axial-force system (a) as long as an element holds the top nodes in place. Pooled chocolate connects branches, buckling of "trunk" poses a structural concern (b). At larger scale, strings take catenary shape and buckling becomes even more of a challenge (c).

Fig. 4. Structural action in a hypar shape, showing hogging (red) and sagging (blue) behavior (a). Shell formed on pre-stressed fabric formwork before (b) and after (c) being taken down from its supports. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
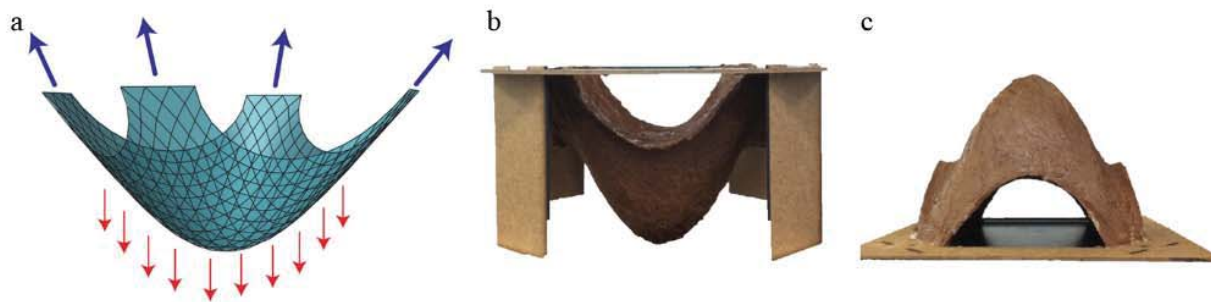
Fig. 5. A suspended cloth subject to only its own self-weight creates a three-dimensional catenary shape in tension (a). This cloth can be covered in chocolate (b) and when hardened and inverted will create a compression only form (c).

To create a saddle in chocolate, elastic fabric with wooden supports were used to create a formwork, upon which chocolate was poured (Fig. 4(b)). Once the chocolate hardened, the shell was removed from the two high supports, but remained integrated into the flexible formwork (Fig. 4(c)). Although successful at a small scale, this construction technique at a larger scale becomes more challenging. The construction method for a saddle would encounter many of same obstacles as construction of a pneumatic shell discussed in Section 2.2.1. The low viscosity of the material and the scale of controlled pouring would require further development of this technique for the construction of a full scale structure. Also, stiff edge beams would be required to bring the loads to the supports, thus reducing the aesthetic elegance and creating additional construction challenges.

2.2.4. Inverted hanging cloth form

The principle behind the inverted hanging cloth method can be understood as the three-dimensional version of Hooke's discovery: a piece of cloth that is hung from several fixed points will create an ideal form that is completely in tension (Fig. 5(a)). For a hanging form in chocolate, a rectangular piece of cheesecloth was suspended from the four corners of a frame. It was then coated in liquid chocolate by pouring chocolate on the cloth and spreading it using a paintbrush (Fig. 5(b)). Once the chocolate set, it was flipped, resulting in a shell in complete compression, as shown in Fig. 5(c). Shell buckling, which can be aggravated by the material's creep behavior, was not accounted for in this form-finding process. However, unlike the branched system, whose buckling behavior was local, this global buckling posed less of a problem due to the double-curved nature of the shell form. From a structural point of view, this form generation technique held the most promise for a chocolate structure as it avoided bending stresses, local element buckling and edge beams.

In terms of construction practicality at a large scale, this method suffers from many of the same drawbacks of the pneumatic and saddle forms. The chocolate does not remain at the place it is applied; in this experiment a majority of the chocolate fell through the cheesecloth at the bottom. The most limiting restriction is the fact that the form must be inverted. If this form finding method were to be used as a construction method, the entire shell would need to be inverted after setting, which becomes a much more difficult task as the scale grows. A much more pragmatic solution is to use the hanging method as a form finding technique, with a more feasible construction method.

2.2.5. Discussion of physical form finding experiments

These material driven explorations for the generation of a constructible and structurally feasible shape for the chocolate pavilion led to the following structural and constructional conclusions. Considering the structural benefits and drawbacks of each family of forms, the inverted hanging cloth form best fit the properties of the chocolate. With only the self-weight of the material to carry, this catenary form was the most structurally efficient. As long as creep and global buckling were considered in design, it provided the system that can span the furthest using the smallest amount of material.

Although the rheological properties of the chocolate were attractive to explore flows of forces by pouring material onto formwork or dipping material, the practicality of this application method would break down at a large scale with a limited construction timeframe. Considerations such as control over material thickness, adherence to support formwork (whether flow over steep formwork or accumulation on a set of strings), the setting speed of chocolate, and assurance of a monolithic form raised large construction challenges. These questions were addressed using pre-fabrication and segmentation techniques that relied on manufacturing of sub-elements in the controlled environment of a chocolate manufacturing plant.

3. Material oriented parametric design methodology

Based on the findings of the physical material driven explorations in shape generation, a structural system was chosen where the form is found using the hanging membrane technique but construction is facilitated via a precast segmental approach. Since the site and boundary conditions were unknown and subject to change, the ability to explore various designs quickly was desired. An integrated parametric workflow was created for shell design that utilized computer aided manufacturing techniques. The parametric programming environment used for this project was Grasshopper 3D, an extension of Rhinoceros 3D. It was chosen not only for its ease of use, but for its plug-in framework that allowed programs with varying functionalities to be combined together to create an integrated system [7]. This integrated process enabled enhanced design exploration and reduced errors in translation of structural models to output data. The parametric form finding, optimization, and detailing procedure is discussed in this section.

3.1. Structural form finding of a single layer grid shell

The physical process of form finding using a hanging cloth can be represented digitally by discretizing the surface into a network of linear elastic springs connected at nodes with free rotation with gravity loading applied at the nodes. This system behaves like a cable net and can only act in pure tension. When inverted, it creates a network in compression. The topology and supports can be adapted to create a large variety of funicular shapes. This method forms the basis for the parametric shape exploration of the chocolate shell. A particle–spring simulation framework allows for
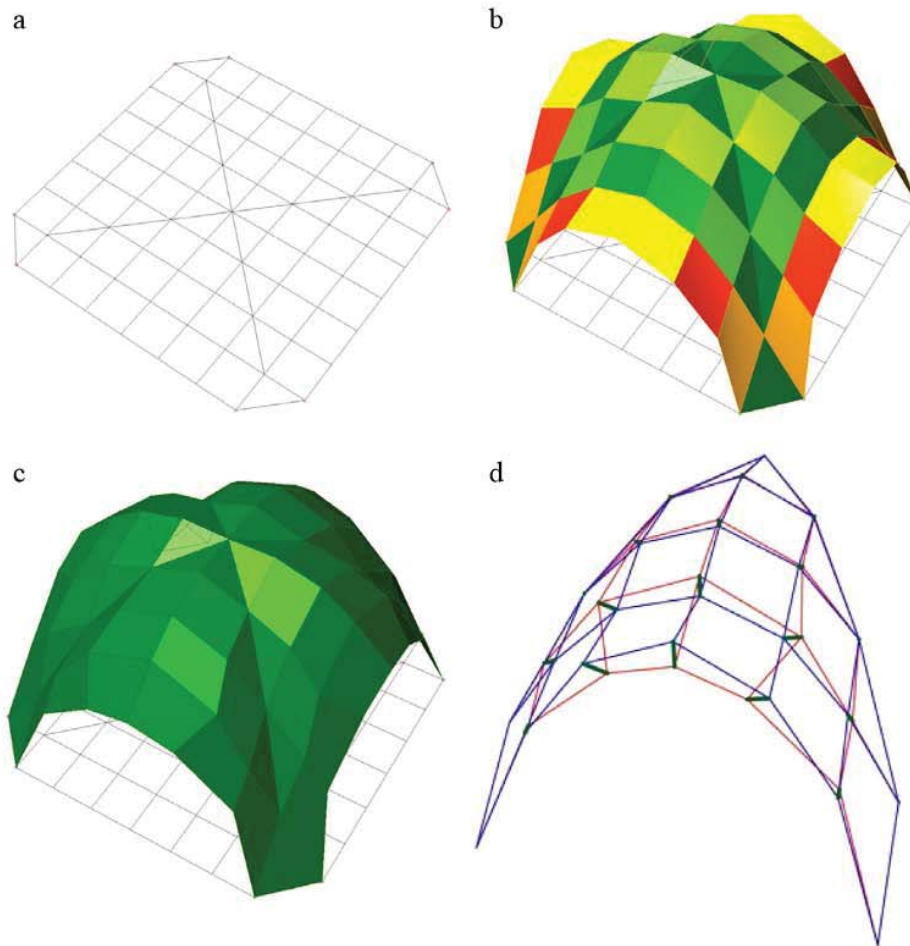
Fig. 6. Digital workflow begins with particle spring form finding from an initial mesh of triangular and quad faces anchored at the 8 corner nodes (a). Inverse gravity forces are applied to the nodes (b), and then the quad faces are made planar (c). Planarity is expressed on a color scale from most planar (green) to least planar (red). Planarity model: zero rest length springs (green) pull the mesh quads (red) towards each quad's best fit plane to make every quad planar (blue) (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interactive computation of the shell form starting from a flat mesh of springs, supports and loads [8]. To implement this particle spring form finding within a parametric framework, the Grasshopper plug-in Kangaroo is used. Kangaroo, a particle spring physics engine, takes in the initial geometry and generates a form found global geometry as the result [9]. In a typical grid shell, this global mesh geometry is realized using a network of linear members connected at nodes. However, this would require manipulation of the mesh to avoid torsion in the members and guarantee planar nodal connections [10]. Instead, the chocolate shell consists of plate elements. The plated shell was first presented by Wester [11] and further developed in the ICD Research Pavilion 2011 [12]. The details of these plates are described in Section 3.2.

To ease construction and guarantee the required material properties, we opt to cast the chocolate in planar molds in a controlled environment. The cooling tunnels impose a maximum mold size of 55.9 cm × 23.5 cm. This manufacturing constraint limits the mesh element dimensions in the form-finding model. Making all faces triangular easily accomplishes the planar mold requirement but impedes design opportunities and adds unnecessary weight and numbers of members. Thus both triangular and quadrilateral faces are used in the mesh geometry. The planarity of each quadrilateral face is achieved within Kangaroo by connecting its nodes to the

nodes of the face's best-fit plane with a spring. This planarization technique introduces forces that do not exist in the physical world and that induce bending into the system. The amount of bending introduced is proportional to the amount the shell needs to be adjusted to make every face planar. Small adjustments add negligible bending, but planarizing an extremely skewed shell may induce significant bending stresses. Fig. 6 illustrates the form-finding and planarization process.

3.2. Member size optimization

The next step in the workflow is to analyze the form found and planarized geometry. This analysis is performed using the Karamba plug-in for Grasshopper, which takes the mesh from Kangaroo and the material properties determined in Section 2.1 and returns the axial and bending stresses in each member [13]. The size of the members in the final shell is optimized using this system, based upon the assumption that the shell will act structurally as a discrete system. Due to this discrete member action, most of the interior area of the plate is removed to reduce self-weight, creating frames with interior voids of variable size, defined by the optimization procedure. The optimization procedure iterates reducing the member size based on the analysis results and repeating the analysis
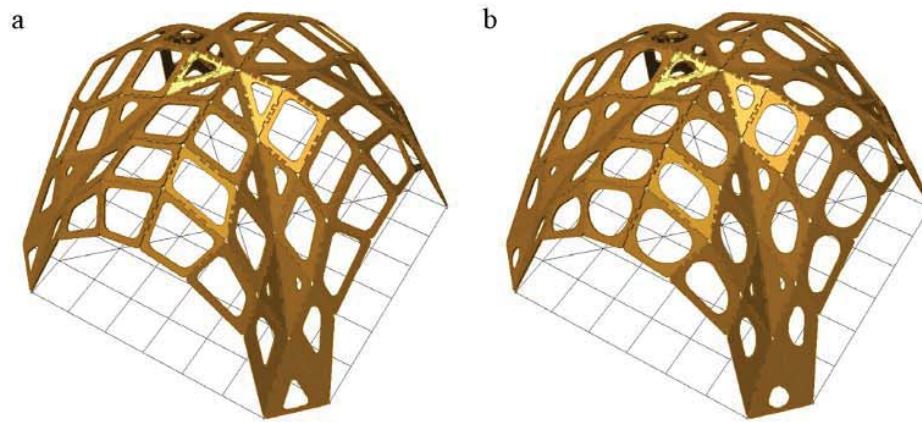
Fig. 7. By changing the parameter controlling the inner fillet radius, the shell can be given a more squared (a) or bubbled (b) aesthetic appearance. A larger radius (b) also increases in-plane moment resistance.

with reduced self-weight. The result is the minimal cross-sectional dimensions of the members that will withstand compressive yield stresses and Euler buckling stresses induced by self-weight. The intersection of two frames creates a common member from the two frame edges. These edges also form the connection between two adjacent frames. In the physical world, a moment connection is needed between the frames to make the pinned grid geometry, a mechanism, into a stable system that can also resist global buckling. This moment-connection is guaranteed by welding chocolate together, unifying the two frame edges in a single V-shaped member. Section 4.2.3 explains the practical details of this welding procedure.

3.3. Detailing and formwork layout

The parametric model in Grasshopper controls not only top level form-finding but also the connection and manufacturing details. It takes the mesh geometry from Kangaroo and the frame width and thickness data from Karamba, and combines them together to produce the final geometry. The workflow also incorporates more parametric details, including number and size of shear tab connection pieces, size and position of construction labeling, and size and layout of molds. For example, one parameter controls the fillet radius on the interior border of each frame. Fig. 7 shows how this fillet value has a significant effect on the visual impact of the shell. Structurally, a larger fillet radius increases the in-plane moment resistance of the frames. The generation of the formwork layout forms an integral part of the digital workflow and is based on the concept behind the cardboard scaffolds, used in the Block Catalan Tile Vault [14].

4. Small scale physical prototype

4.1. Physical prototypes

Existing large-scale chocolate artifacts are mostly representational sculptures, not performance-driven structures. Structurally, they rely on "mass" rather than "form" to carry their self-weight. With no prior published numerical, experimental or analytical results for large scale chocolate structures, creating prototypes are essential to (i) validate the feasibility of the proposed design and construction approach and (ii) confirm that the shell does not exhibit creep-triggered buckling or other additional unpredicted structural failure mechanisms.

4.2. Proof of concept for parametric methodology

4.2.1. Segmented global geometry

A 1:6 scale prototype of the chocolate structural system was developed using the workflow described in Section 3. The initial mesh was developed on a square grid of 8 by 8 faces, supported on its 4 corners, intended to cover a square plan area of 80 cm × 80 cm. The scale was chosen so that the mold and scaffolding components fit the laser cutter bed and the structurally needed thickness of the chocolate fit the scale of the molds. To reduce stress concentrations and provide a more substantial support area, the corner faces were cut off diagonally, creating V-shaped "feet" to give each corner two points of support. Diagonal ribs were introduced to reduce the central apex height and bring it closer to the central height of the boundary arches, which, in the full scale design, were scaled for human occupancy to be 2.5 m tall.

This 4-way rotationally symmetric design reduced the number of unique molds from 76 to 19. Finger joints were included to facilitate construction precision and stress transfer between the pieces, but the tabs disrupted the symmetry of the pieces. Thus, 9 sets of molds were mirror images of each other. Each piece was given three pairs of shear tabs per side. Each tab was given a depth double the thickness of the piece and a width of 10% of the side length. The pieces were prismatic, and mesh was designed to be "thickened" outward. Thus, the exterior fillet needed to be tuned to avoid material intersections at the mesh vertices where four pieces came together at varying angles. The inner fillet was tuned to make the voids look more rounded and provide sufficient in-plane moment resistance. Special care was taken in the detailing of the triangular frames that create the ribs of the pavilion. When viewed from the outside, the rib angle was concave instead of convex. This meant material needed to be taken away from those frame edges to avoid material intersection. The prototype consisted of 76 chocolate pieces with a thickness of 6 mm and weighed approximately 15 kg or 0.25 kN/m^2.

4.2.2. Molds and formwork

Even though the structural chocolate would not be eaten, the molds needed to satisfy sanitary requirements to avoid contaminating the other chocolate in the production facility. Additionally, the molds needed to be designed to allow for fast and inexpensive production. The small scale of the chocolate pieces lent itself to laser cutting the molds to exact specifications. Since acrylic is nonporous and can be cut by the laser cutter without distortion up to thicknesses of 6 mm it was the preferred mold material. The molds'
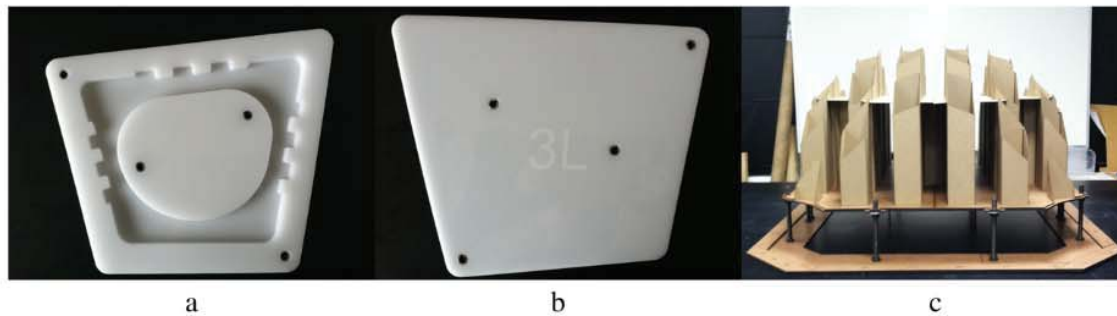
Fig. 8. The molds sit flat with recessed spring pins so nothing protrudes from either side (a) front, (b) back. The formwork assembled and in position for shell elements to be placed (c).

Fig. 9. Large scale molds made from CNC milled Styrofoam. Styrofoam lined with contact paper and the interior wall is flexible for easy release (a). This type of mold is inexpensive and reusable (b).

nonporous property meant that the chocolate released easily and the molds were safe for food production, since no splinters or dust were released. The non-uniform geometry of the pieces, especially with the shear tabs, dictated a two-part mold design. The prototype molds consisted of a back plate with a plate with the piece geometry cut through it on top. Thus the cut edge of the acrylic provided the side surface of the mold. An "island" was then placed in the center to create the void as shown in Fig. 8(a) and (b).

The two objectives of the scaffold design were decentering of the shell without lifting or moving it, and decentering the entire shell simultaneously to avoid partial loading. A base ring served the dual purpose of providing a foundation and ensuring that the formwork was precisely positioned in relation to the shell feet. A nut and bolt mechanism raised and lowered the cardboard formwork by screw action (Fig. 8(c)). Once the shell was constructed, a team of 4 people could decenter the shell using the screw mechanism. The individual formwork supports could be lifted out and the mechanism disassembled without disturbing the shell, leaving just the foundation ring.

Since the pieces for a large scale shell would be both larger and thicker, a different mold design was required. Acrylic becomes prohibitively expensive at large sizes and thicknesses. Since wood is prohibited as a mold material due to splinters, extruded polystyrene (Styrofoam) was chosen. Styrofoam is very inexpensive even at large thicknesses, easy to CNC mill, and, when lined with contact paper, does not adhere to chocolate. While setting, the chocolate would shrink, often getting stuck around the mold "island". This phenomenon manifested itself as a much larger problem in the large scale molds. To overcome this problem of chocolate contraction, the inner wall was made flexible by removing the majority of the "island" and cutting pressure release notches as shown in Fig. 9(a). This detail allowed the inner wall to move inwards when the chocolate set. Once the chocolate piece is lifted out, the wall would return to its natural position and the mold could be reused. To facilitate quick erection, a pre-assembly system was devised whereby multiple pieces are joined into assemblages using smaller formworks that can continuously support every seam to ensure precision and constrain the weld. With a lesser number of these assemblages, the amount of welding needed on site would be greatly reduced, and only the seams between assemblages would need continuous support.

4.2.3. Casting and assembly

To allow for the required degree of precision in manufacturing, the individual pieces were prepared and cast in the controlled environment of the chocolate manufacturing plant. The casting procedure was the same as the procedure to make the material test samples (discussed in Section 2.1), in an attempt to recreate the same material properties. With chocolate melted at 52 °C and mixed thoroughly, the molds were filled and scraped flat (as shown in Fig. 10(a)) and then refrigerated at 4 °C for an hour. At the prototype scale, the pieces came out of the mold by simply tapping them (Fig. 10(b)).

Once all pieces were manufactured and transported in temperature-controlled conditions to site, they were assembled on the formwork. The indoor site has a constant temperature of 20 °C, 32 °C below the material's melting point. The corner supports were set and welded in the prepared foundation ring using
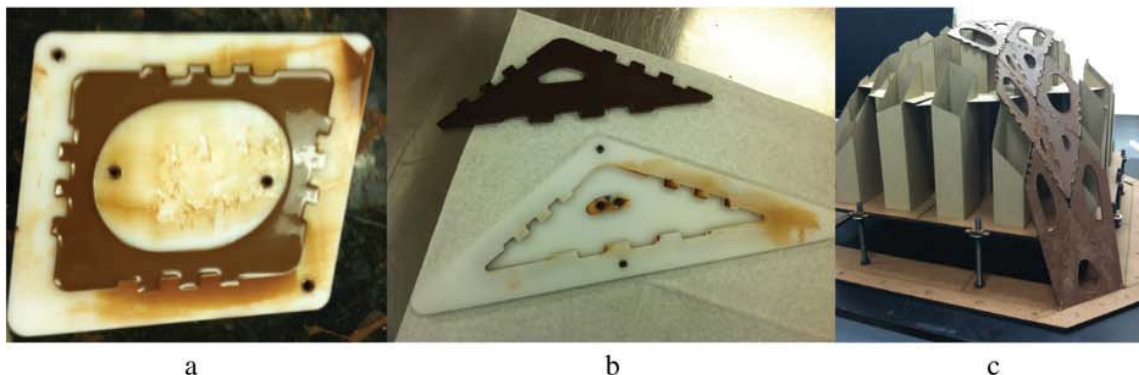
Fig. 10. Acrylic molds are filled with chocolate and scraped flat (a). Once set, the chocolate releases from the mold easily (b). The pieces are then assembled on the formwork, beginning with the ribs (c).

molten chocolate. As the interior rib seams could only be accessed from the interior, the ribs seams were welded first, then placed as shown in Fig. 10(c). Afterwards, the rest of the pieces were filled in, which fit very tightly together with the shear tabs. This tightness meant that the assembly was very precise, but also that cracks and even breakages of the tabs occurred due to the considerable pressure applied to fit the tabs together. In order to address this issue of cracking and breaking of the shear tabs, they were eliminated from the large scale piece design altogether (see Fig. 9(b)).

Once all pieces were placed, there was enough slack in the system to ensure all pieces were sitting evenly on the formwork and all seams were lined up. The seams were welded using a syringe to deposit the molten chocolate. When those connections set, the shell gained considerable stiffness, having turned the hinged system into a fixed one. The formwork was gradually and uniformly decentered and the prototype shell stood free (see Fig. 11). During a two-month time period the prototype was exhibited at 20 °C. No creep behavior was observed, which gave us sufficient confidence that at a larger scale for a shorter exhibition period of 2 weeks in a similarly temperature controlled room, creep would not be an issue.

5. Application of parametric methodology for a café pavilion

The first full-scale use of this chocolate design methodology is a pavilion for a café space, still awaiting construction. This pavilion will be on display for 2–4 weeks in a temperature-controlled environment. The café inhabits an open plan double height space in a typical New York City building. To avoid exposure to direct sunlight coming through the south-facing windows, obstruction of customers and staff traffic, and accidental collisions, the shell was designed to use the vertical space and span between the fixed partitions that separate the café's tables. The integrated design methodology presented in Section 3 allows radical changes in the shell's geometry from the prototype. The workflow allows interactive generation and exploration of a realm of feasible and constructible chocolate shell shapes (see Fig. 12(a) and (b)). In the course of the design process, the client imposed two additional restrictions, which necessitated a drastic cutback in the proposed designs. The pavilion could no longer be supported on the partitions and the entire on-site construction time was limited to one night (i.e. 8 h). With these additional restrictions, the design changed. It would be supported on temporary platforms clamped to the structural columns, spaced at 3.75 m intervals. The narrow base and the long span favored the design of a shell arch rather than a spatial shell (see Fig. 13). As a result, fewer chocolate pieces were needed, which would speed up construction time. The angled footprint of
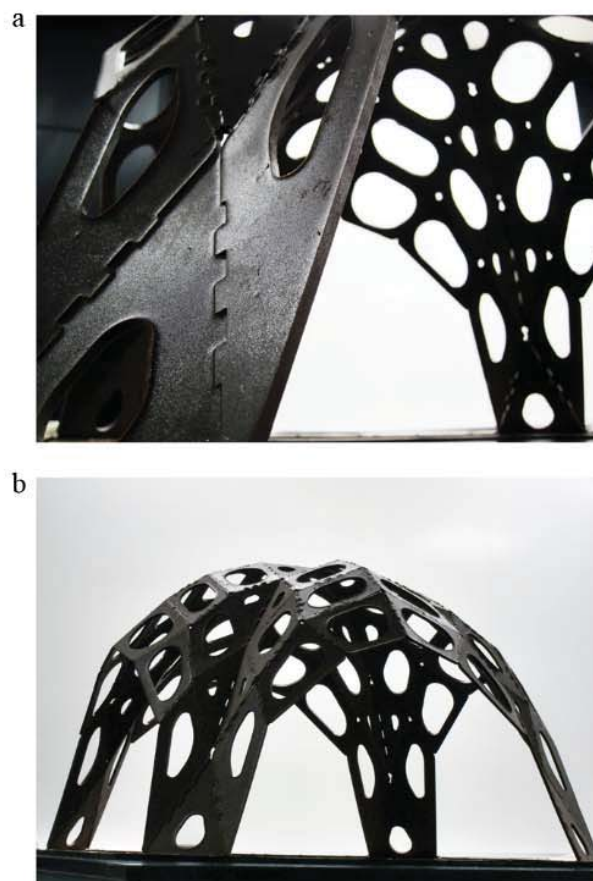

Fig. 11. Shear tabs on the individual pieces ensure precise assembly (a). Once decentered, the grid shell spans 80 cm with pieces only 6 mm thick (b).

the chosen design would increase stability, since the structure was reduced to two supports. Although modest, this pavilion will act as a proof of concept for large scale chocolate structures.

6. Discussion

This chocolate pavilion study represents form finding not only as a purely structural performance driven process, but it also considers the much harder to quantify character of a material and how

a   b

Fig. 12. Volumetric (a) and linear (b) design proposals for a chocolate pavilion that rests on partitions between tables.
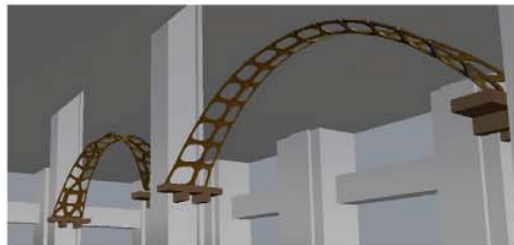

Fig. 13. Two designs for chocolate arches that span the 3.75 m between structural columns, resting on temporary platforms.

it is best expressed through form. Following material properties can influence the shaping of form. Yet, a harder question is which form is most fitting for a material from an overall expression. The pouring and dripping traces of the early experiments held promise but are difficult to translate through the scaling up of the model. Force-modeled shell shapes are beneficial because of their ability to resist external loading because of their force driven curved form. In an unfamiliar building material, like chocolate, established design and construction processes need to be revisited and adjusted. Although we have associations with chocolate as a highly refined food, there are few precedents of how to translate its familiar sensation into architectural and engineering language. This was the motivation for the series of pour, dip and stack experiments. Rigorous physical experiments reveal its equally low load-bearing compressive and tensile capacity and its tendency towards creep under sustained compressive loads. The rheology of the chocolate suggests the exploration of four physical methods that generate material-driven force-modeled shapes. These design exercises inform us about the potential and the feasibility of these techniques as form generators and construction methods. An approach that integrates an inverted hanging cloth model as a form, chocolate as a material, a segmented grid shell as a structure and pre-fabrication as a manufacturing technique, emerges and finds its way into a parametric digital design to construction workflow.

By applying existing form finding and optimization techniques within a parametric formwork tailored to meet specific site constraints, the designer has the freedom to explore and play with a realm of efficient and constructible forms, brought forth by the intrinsic qualities of chocolate. The success of the design is very much in the designer's hands—factors from the initial geometry to the various choices made during the design process affect the efficiency of the result. For example, a initial mesh with skewed edges will need to be highly planarized and will end up needing to be thicker or have larger flanges for the same span. Another example is that the choice of initial mesh density means a tradeoff between number of molds and size of members. This understanding

expands into the concept of discipline and play, the terminology used to describe the conflict of emphasis that distinguished early shell designers [15]. In a sense, this system provides both—the parametric framework imposes the discipline, while leaving the designer the freedom to play with form. The chocolate material builds on this idea of play—the designer is looking for ways to express the material within the design in an experimental fashion.

This exploration of material proves important to choosing forms that express structural and aesthetic values, not just for Willy Wonka, but for designers who wish to engage in material-driven design exploration.

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