CILAMCE 2017

Florianópolis - Santa Catarina - Brazil

THE IMPACT OF PNEUMATIC AND CATENARY FORMS ON THE DESIGN OF THIN CONCRETE SHELLS

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Abstract. *A recent decline in the construction of thin concrete shells may be due to the intensive labor that surrounds its complicated formwork. This paper begins to examine potential new methods to revitalize the concrete shell industry by analyzing the application of pneumatics. To investigate these modern practices, including the PFHC technique and beyond, an original design for a thin concrete shell was drafted. The ANSYS finite element software was utilized to obtain both pneumatic and catenary forms from the same initial material properties and boundary conditions. Stiffness and applied loads were altered in several portions of the geometry in order to achieve aesthetic and optimal designs. We would expect both the pneumatic and catenary shapes to appear somewhat similar, yet given the nature of their respective loadings,* *the principal stress distribution should differ. The degree to which these discrepancies exist, and their respective implications on the structural integrity of these concrete shells, will be examined thoroughly with virtual and physical models.*

Keywords: *Thin Concrete Shells, Pneumatic and Catenary Forms, Finite Element Modeling, Patterning, Numerical Modeling*

1 INTRODUCTION

The era of the thin concrete shell has been waning for decades. "Missing guidelines and design rules, the non-coverage of high-performance materials in the building codes and fragmentary cost-calculations, not considering life-cycle costs, are accumulating risks that architects, engineers, clients and contractors are not willing to bear," (Eisenbach, 2017) so recently, these concrete shells are not at the forefront of the minds of city planners. However, recent strides in structural engineering have shown that this may no longer be the case in the future.

2 STRUCTURAL APPLICATIONS OF THIN CONCRETE SHELLS

2.1 Catenaries and Pneumatics

Most shells are derived from one of two conceptual ideals: catenaries, or pneumatics.

Catenary forms are used to create resistance to gravity loads. They stem from the shape of an object, typically a rope or fabric, undergoing self-weight while being supported at its ends. In other words, this form is entirely dependent on the mass and density of the material. After obtaining this "sagging" form, the geometry is inverted.

Many assume that catenary structures classify as parabolic due to their striking similarity in shape. In actuality, the geometry is more akin to a hyperbolic cosine. It is important to make this distinction as the difference in form is often neglected, or deemed as benign. This discrepancy, however, could lead to potential structural issues in the construction of large-scale shells.

Pneumatic shapes, on the other hand, are known to combat wind forces and maintain equilibrium under the presence of these loads. These forms come about by an outward pressure that acts normal to the faces of the shell, similar to the inflation of a balloon. It is to be expected that the resulting geometry should differ considerably from a catenary, considering that these force vectors will be changing their direction instantaneously so as to coincide with the normals of the shell faces.

2.2 Construction Methods and Structural Implications

The golden age of the construction of doubly curved concrete shells occurred from the 1920s to the 1960s (Rippman, 2016). Engineers like Heinz Isler popularized the hanging-membrane technique, which is the easiest shape to approximate for design purposes, especially in the case of small-scale formwork. Although this catenary method ensures that the concrete shell would only be subject to compressive forces, rather than tensile (in which concrete has relatively low strength), bending and torsion moments were often left unaccounted for (Hernandez-Montes et al., 2014). As such, the lack of adequate form-finding calls upon the need for steel reinforcements. Nevertheless, engineers are still experiencing difficulties with creating the complicated formwork and deriving reinforcements that simultaneously counteract both membrane forces and bending moments (Hernandez-Montes et al., 2014). From a structural perspective, the concrete shells could be designed in a much more efficient manner so as to adequately utilize the material properties.

Most shells contain doubly curved surfaces, which are also known as positive Gaussian surfaces. The main issue concerning this geometry is that these surfaces are not developable. Similar to a sphere, it is impossible to flatten the shape without major distortion or flaring. Ergo, complex formwork is a given.

A potential answer to this design challenge is the application of pneumatic formwork. Pneumatic formwork was first patented in 1926 for the production of culverts and concrete pipes; this involved the inflation of a cylindrical membrane coupled with the setting of workable concrete molded around it, eventually culminating in the rupture and removal of the membrane (Kromoser and Huber, 2016). This innovation has since developed into a novel technique known as the Pneumatic Formation of Hardened Concrete (PFHC), which aims to ease the creation of positive Gaussian surfaces. Using the PFHC method, an initially flat plate of concrete, consisting of panels, is poured in the shape of the "flattened" final geometry. An air-tight membrane lying under the the concrete layer is then inflated to apply an outward pressure, lifting and deforming the panels until the desired shape is formed. This method is particularly novel in the sense that, regardless of the final conjoined body, the composite plates will only undergo a curvature change in one direction, which respects the deformation capacity of the concrete.

The PFHC method is still relatively new, and as such, it has only been applied to shells with very basic geometry. Therefore, there is potential room for more advanced applications of the technique, and with pneumatic membranes in general.

3 DESIGNING AND FORM-FINDING PROCESSES

An original large-scale pear-shaped concrete shell, intended to serve as a pavilion, has been drafted in several computer-aided design programs.

3. 1 Sketching and Meshing

ANSYS AIM 18.0 was the primary software chosen for virtual model creation. This program is capable of running static structural simulations, so coupling this with its capacity for finite element analysis makes it an excellent candidate for the designing and form-finding stages.

The initial step was to assign sufficient material properties in order to simulate membrane behavior. In order to do so, the element type "SHELL181" was selected for its large strain nonlinear capabilities. The deflection settings were adjusted accordingly by setting this parameter to "High."

Next, a two-dimensional model was designed in ANSYS SpaceClaim. This geometry would serve as the footprint of the final shell, regardless of the form finding technique. A symmetric boundary shape was obtained by drawing two circles of different radii and splicing them together using three-point curves; the resulting form is reminiscent of a pear. Once this edge was constructed, the plane space within the curves was partitioned into 20 regions by using line segments that emanate from the centers of the drafting circles (see Fig. 1). This was done in order to achieve more symmetry and proper node edges during the mesh creation process.

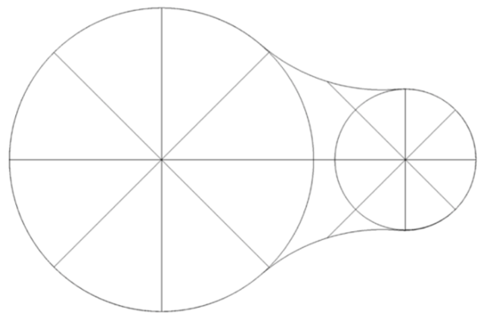

Figure 1. The pear-shaped shell footprint.

The flat plane was arbitrarily chosen to span 23 m by 15 m. In the ANSYS Mechanical software, the geometry was assigned a thickness of 7.5 cm in order to satisfy a typical span/thickness ratio of 200 (Eisenbach, 2017).

A command was inputted to generate a coarse, yet refined mesh. Following this, all edge segments of the plane were assigned a fixed displacement so that they wouldn't shift in the x-, y-, or z-direction while subject to forces.

3.2 Schematics in ANSYS

The loading stage would differ for the pneumatic and catenary models, so the pear plane geometry was copied into a separate schematic so as to run two simulations simultaneously.

In the case of the pneumatic model, a force of 1000 Pa was applied normal to the face of all nodes. This is to say that for every iteration of the static test, the force vectors would adjust in direction to compensate for the constantly shifting and warping elements. After 100 time substeps, approximate convergence was achieved, so the final structure ceased to expand further outwards and was frozen into its "inflated" state. The viewfinder's magnitude was amplified by a factor of 40 in order to exaggerate the form. From observation alone, the pneumatic shell was extremely smooth and appeared rather spherical towards its center points (see Fig. 1.4).

The catenary schematic also featured an imposed force, but in this case, the vectors were intended to emulate self-weight via a gravity load. As such, during the simulation, the force vectors always ran upward (rather than downward for orientation purposes) in a parallel fashion, regardless of element deformation. In order to reach convergence, the number of substeps was increased from 100 to 500. After running the simulation, this resultant form was also locked. Again, the magnitude of the viewfinder was adjusted accordingly.

There were multiple iterations of the pneumatic and catenary schematics, which is to say that the deformed geometry was tweaked until an aesthetically-pleasing and satisfactory form was reached. In essence, each shell ran through the static structural simulation, only to be plugged into a new schematic at the end for more tests and further refinement. There were times in which portions of the shell appeared too flat, too rounded, or too warped, so modifications were necessary. This took the form of editing the spring stiffness among the elements, the Young's Modulus, the Poisson's Ratio, and the material thickness. Although these properties may have deviated from the actual characteristic of concrete, these changes were warranted in the name of form-finding. The differences brought about by these changes were substantial enough to make the shells appear sleeker and smoother to the eye.

Once the pneumatic and catenary designs were finalized and placed into their last schematics, the material properties were reverted to their original state for conclusive testing.

3.3 Resulting Catenary and Pneumatic Stress Distributions

Below are some images of the resultant shell forms and their corresponding deformations and stresses. The catenary shell is on the left, and the pneumatic shell is on the right.

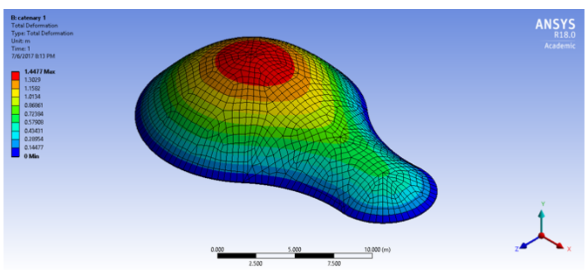

Figure 2.1

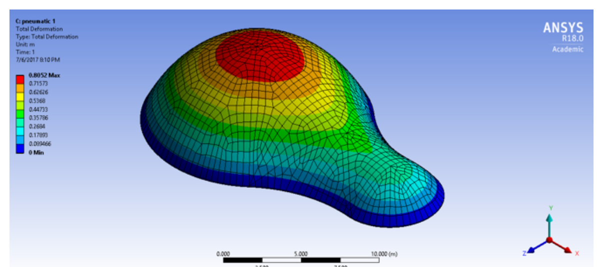

Figure 2.4

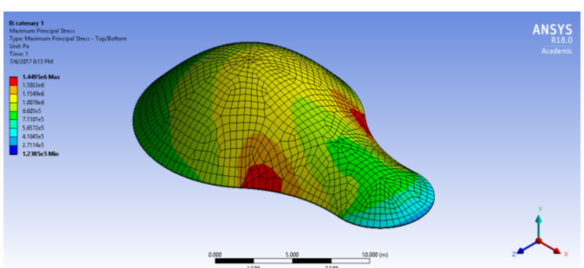

Figure 2.2

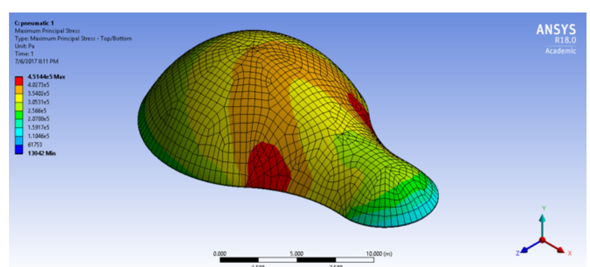

Figure 2.5

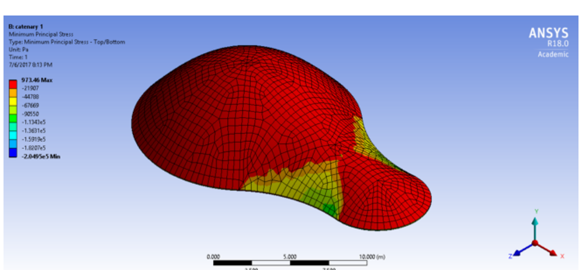

Figure 2.3

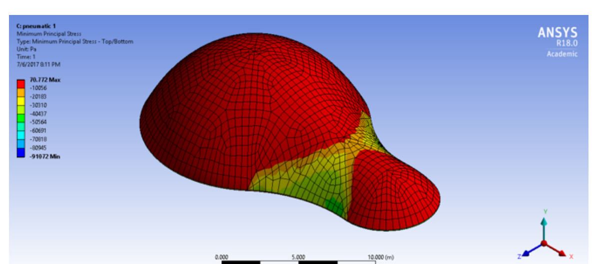

Figure 2.6

Table 1. Deformation and stress range comparisons

	CATENARY SHELL	*PNEUMATIC SHELL*
TOTAL DEFORMATION (M)	**1.4477 to 0** (Fig. 2.1)	**0.8052 to 0** (Fig. 2.4)
MAXIMUM PRINCIPAL STRESS (PA)	**1.4495e6 to 1.2385e5** (Fig. 2.2)	**4.5144e5 to 13042** (Fig. 2.5)
MINIMUM PRINCIPAL STRESS (PA)	**973.46 to -2.0495e5** (Fig. 2.3)	**70.772 to -91072** (Fig. 2.6)

*Note - The underlined figures represent the maximum values.

Aesthetically, the pneumatic membrane has a more rounded shape, and the catenary shell has somewhat of a tapering flattened edge. The pneumatic membrane would be more ideal in the case of maximizing the interior space of the pavilion.

The difference in deformation can be neglected due to the varying magnitude of the applied forces; the pneumatic model underwent a consistent force of 1000 Pa, whereas the catenary shell was subject to its considerably greater self-weight. Additionally, the true deflection of the elements should not be taken into account because the desired forms were magnified independently by the viewfinder. If, for example, the catenary shell was magnified at the same scale as the pneumatic figure, the shape would become unaesthetically exaggerated and appear rather conic in nature.

The order of magnitude of the deformation and stresses in the catenary shell were quite extreme when compared to that of the pneumatic form. Although wind loads and gravity loads are both form-finding parameters, gravity loads are overwhelmingly the dominant force required to be resisted by the shape, construction, and foundation of the shell. This is mainly due to the concrete's material properties. As such, if using the catenary deformation as formwork, the shell could hypothetically bear a greater degree of loads. The associated stress distribution, however, should be taken into consideration.

Note that the range of the maximum principal stress in the catenary shell is limited when compared to that in the pneumatic shell. Even so, the catenary shell features areas of intense stress concentration, reaching over 10^6 Pa in the "neck" of the form because of the curvature change (see the red/orange swells in Fig. 2.2.). To compensate for this, varying spring stiffnesses towards the base could allow for the spread of reaction forces over multiple support points (Jungjohann and Woodington, 2016), although this would call for extra labor. The stress distribution in the pneumatic shell, on the other hand, is much more gradual, which implies that the poured concrete would experience comparatively less strain after construction is completed

From a structural standpoint, the properties and characteristics of the pneumatic shell held more promise, so this design was chosen for subsequent modeling.

4 PATTERNING AND THE PHYSICAL MODEL

4.1 Transitioning from ANSYS to Rhinoceros

In order to create a physical model, the mesh of the deformed pneumatic shell needed to be manipulated in Rhinoceros, a 3D modeling software.

The shell was exported as an STL file from ANSYS and was subsequently opened in the new program. By using the "Contour" command, Rhino was able to draft contour lines in both the x- and y-directions along the mesh. This effectively split the mesh about its symmetry line and sliced the object normal to this line, partitioning the surface into 26 areas.

After splitting the shell into these separate regions, the "Squish" command was applied to each of the areas. This action aims to convert any three-dimensional surface into a two-dimensional developable one, although there tends to be a considerable amount of distortion. Hence, further partitioning of the shell would actually aid in minimizing this error. However, in order to reduce the complexity and the amount of manual labor, the original lines of separation were kept unaltered.

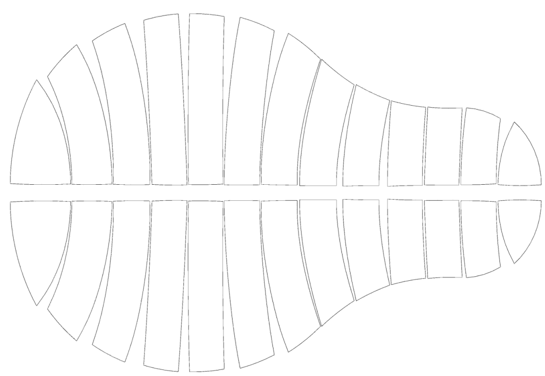

Figure 3. The "squished" two-dimensional pattern for approximating the three-dimensional pneumatic pear shell.

4.2 Small-Scale Paper Model

In order to verify the accuracy of this technique, the patterning in Fig. 3 was printed onto a sheet of paper and cut along its boundary lines. Each segment was numbered and taped to its respective adjacent pieces until the final approximated shape was reached (see Fig. 4). This practice proves that the PFHC technique would hypothetically work as a construction method, given that the panels are only curved in one direction.

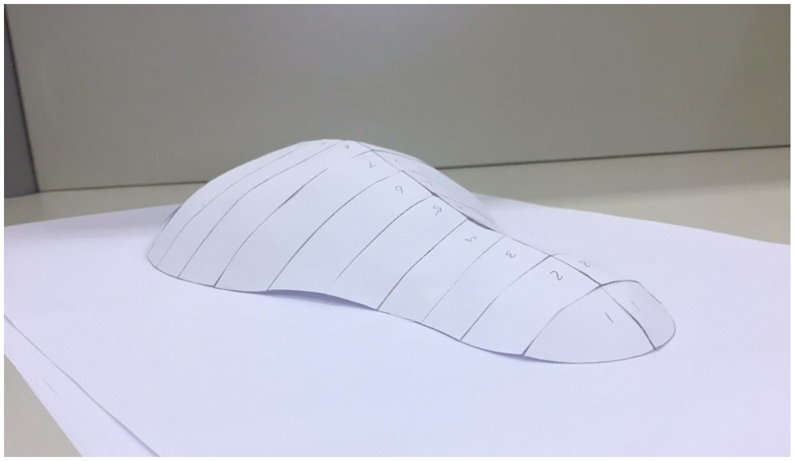

Figure 4. A small-scale paper model of the pear shell.

Moving forward, it would be more conducive to constrict the boundary of the shell's base, for stability and strength purposes. Moreover, overlapping should be included within the patterning. When building a fabric for the plaster model, there needs to be some overhang in order to properly inflate the material to the desired form. Otherwise, air leakage might occur and the fabric may wrinkle and give under certain loads.

4.3 Small-Scale Plaster / Concrete Model

A small-scale physical model was constructed in order to simulate the pneumatic formwork systems. A thin membrane was fixed in a plate by means of a flange having the pear-shaped perimeter designed in this work. After that, the membrane was filled with air and served as the supporting structure.

The flat plane of the physical model was chosen to span 0.60 m by 0.40 m. Initially, the 4 cm wide flange was produced using a CNC milling machine (see Fig. 5a). Then, the flange and the base plate were drilled together (Fig. 5b). To improve the airtightness of the model, the flange was equipped with a rubber seal (Fig. 5c) and the base plate was plasticized. A clear plastic film was used as the membrane. The air insufflation tests demonstrated that the membrane reaches the desired shape (Fig. 5d), evidencing that the higher tensions occur in the hoop direction, as expected. However, the model did not demonstrate sufficient airtightness to apply the shotcrete, and consequently to cast the shell. After 3 hours the membrane presented visible loss of pressure, insufficient time for support and cure of the shotcrete.

The authors continue to work on the improvement of the model, especially in regards to the guarantee of the necessary pressure for shotcrete -- in other words, in the development of a technology that allows for the construction of concrete shells with pneumatic formwork systems.

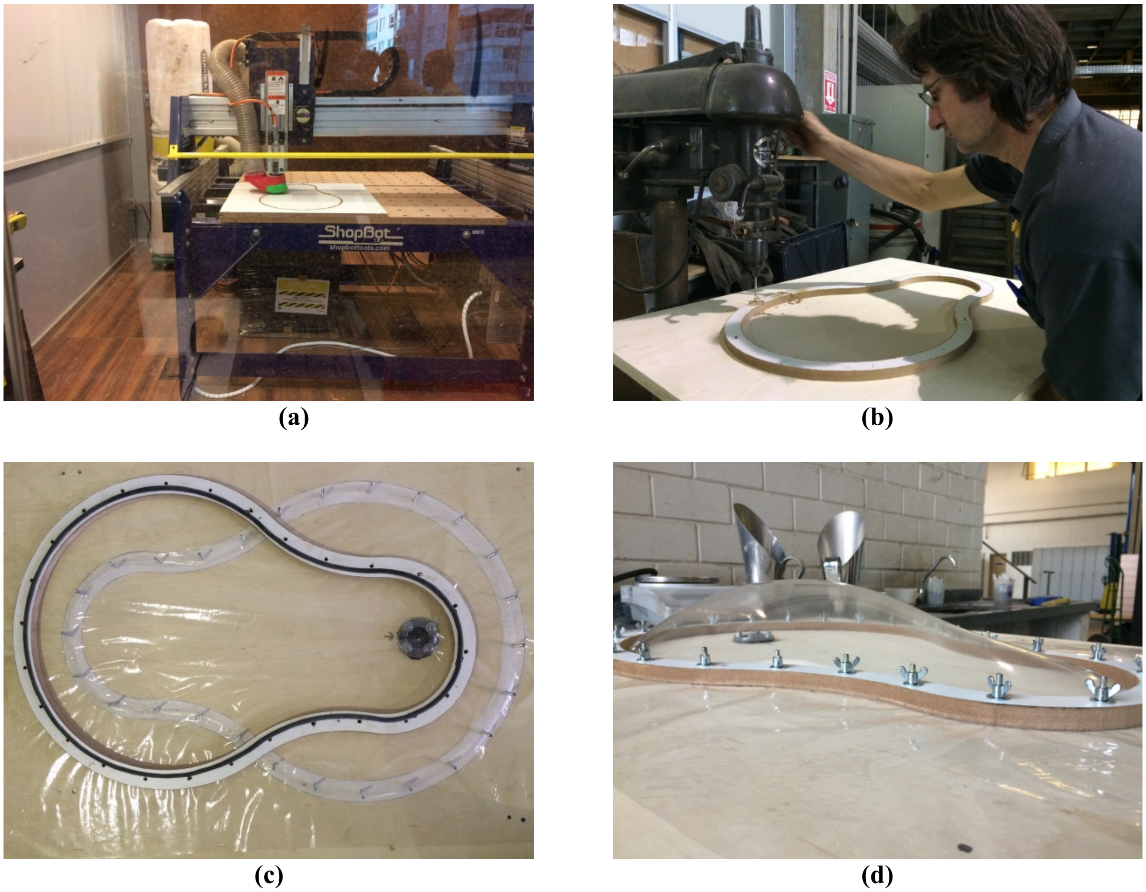

Figure 5. Physical model: (a) CNC cutting the flange; (b) assembly of the flange and the base plate; (c) application of rubber padding; and (d) inflated membrane.

5 SUMMARY

Although this research is still within its initial stages, the fundamentals of architecture will be combined with structure and fabrication in future models and further iterations of the concrete shell design. Pneumatics may hold the key to revitalizing the creation of concrete shells, as it advantageously uses the full extent of the material properties. Further results regarding the physical models will be presented at the CILAMCE 2017 Mini Symposium. A deeper numerical analysis of the structural integrity implications will also continue in the coming months as this project develops.

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