Twisted Mind – A New Concrete Playbook

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Figure 1: Prototype Pop-Up 'Shell' (Photograph by Author).

A Twisted Mind is the playful pursuit of popping up and twisting a concrete formwork that radically challenges the rules of how to build with concrete; a new 'playbook' on how thin shell concrete geometries can be made. This method of making begins with formwork, not the form. Traditional rules of how one designs and constructs a concrete shell no longer applies. Complex concrete forms, like shells or folded roof plates can be produced with comparatively simple twistable, bendable, creasable, foldable elements; a new play on formwork for building elements. The paper discusses how recent advancements in concrete technology, in combination with digital design tools, holds the potential for a new concrete 'playbook' that twists and folds concrete; resulting in infinite 'pop-up' techniques for fabrication and assembly of concrete shell structures.

The method is developed in collaboration with CEMEX Global R&D, a cement manufacturer. Typically, complex concrete structures, such as shells, require elaborate and expensive formwork and reinforcement. 'Pop-up' is a method of using thin, high performance concrete with a formwork that begins as a flat surface and is folded and popped up into a final form during the curing process. The method begins with digital modeling that is recalibrated into a 'foldable' formwork that can be infinitely altered to various configurations, depending on its material properties. This paper aims to show how the 'pop-up' technique can re-play the construction of concrete shells (Figure 1).

INTRODUCTION

Roof structures of thin-shell concrete, such as Felix Candela's Los Manantiales Restaurant[1] or Heinz Isler's Tennis Centers[2], are a prototypical product of the twentieth century, but they were not seen much at the start of the present century[3]. Although, the introduction of digital technology in structural computation in the late twentieth century radically widened

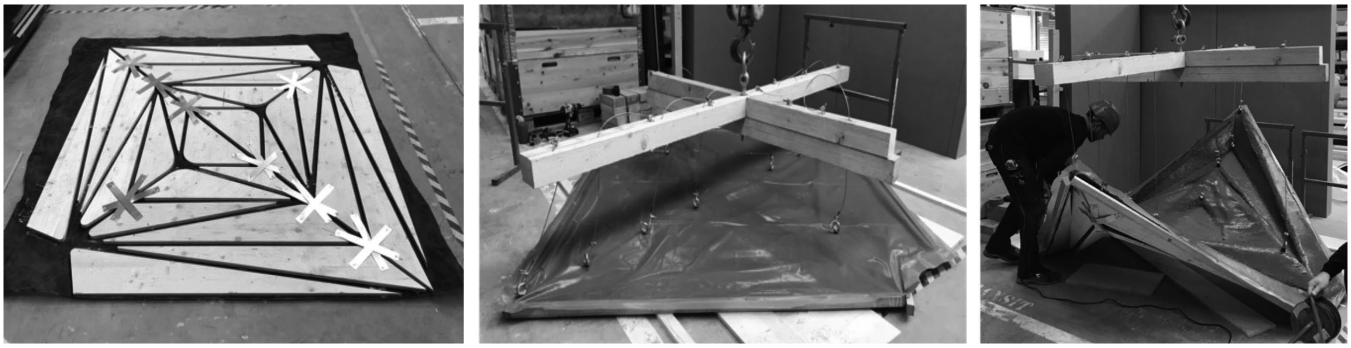

Figure 2: Left: Grasshopper model simulating the 'pop-up' technique from a flat surface to a 'creased' shell form. Right: Initial small scale test showing concrete poured onto hinged, flat formwork which is 'creased' and pulled up into the final shell form (Photograph by Cemex and Author).

the range of possible geometries in thin shell design[4], the techniques of shell construction have not advanced at the same pace. For example, Mutsuro Sasaki's engineering for Toyo Ito's complex shell roof for the Cemetery in Kakamigahara uses sensitivity analysis based on advanced structural computation to optimize the form and material use[5]. However, the construction of this complex shell still required traditional formwork and reinforcement, not unlike the construction methods deployed by Candela or Isler 50 years prior. This results in the fabrication of rather complex false work and formwork made of custom timber construction, as well as the necessary complicated reinforcement patterns.

Recent projects, such as Block Research Group or Culver & Sarafian's concrete shells aim to create complex computational geometry, while simultaneously challenging the fabrication methods of shell construction to significantly reduce material and labor costs. Culver & Sarafian demonstrate the use of industrial robots that are capable of generating various cast components for grid shells based on digital input to facilitate otherwise cost-prohibitive design[6]. Block Research Group uses a reusable net formwork to eliminate the typical wood false work and formwork; thus, potentially reducing the cost of construction and making it possible to envision a wide range of anticlastic shapes [7].

Building upon the aim of the above projects, the described work seeks to revisit the construction of a concrete shell through the 'pop-up' formwork process; a technique that dramatically reduces material and labor while still achieving complex geometries. The project uses fiber reinforced high performance, lightweight concrete that is cast onto flat formwork and folded into shape during the curing process. The technique significantly reduces the complexity of the formwork and potentially eliminates the need for mesh reinforcement.

THE POP-UP FORMWORK

'Folding' in concrete has been a fundamental principle to increase the strength and stability of structural elements. 'Folding' increases a material's structural capacity without having to increase the amount of material used or strengthening it. Although there are many folded structures made of concrete, there has always been a schism between the material and the technique. For example, contrary to sheet metal, concrete is not inherently a flat material but a viscous one that is poured to take a 'folded' shape for structural benefits. Therefore, the construction of a folded concrete form requires a complex formwork that is not actually folded, but does create a folded form for the concrete to be cast in.

However, with the advancement in the concrete mix designs of CEMEX and the improvements to the performance of fiber reinforcement, it is possible for a formwork to fold into infinite forms and positions while the concrete is still curing. This is the basis for the 'pop-up' method that casts concrete in a flat formwork and then positions the formwork into its final form in the early stages of curing

The benefits to the 'pop-up' construction method are threefold. First, this method uses considerably less false work and formwork to create complex geometries. Second, a singular formwork can be computational controlled and altered after each pour to create a variety of elements that vary in height, width, or depth. Third, traditional concrete cannot be 'popped-up' because it is either initially too fluid or, once cured, becomes too brittle; therefore, requiring reinforcement be formed into the shape of the final form prior to casting. Since fiber reinforced concrete does not have the tedious task of shaping and positioning reinforcement within the formwork, the 'pop-up' technique can significantly reduce labor and material costs while still achieving a complex computational geometry.

METHODS

To test the 'pop-up' techniques, a version of a hyperbolic paraboloid shell was used as a basis for the first prototype. The form of the prototype addresses the tension between the computational form and the needed alterations to make the form into a formwork and the final cast. Where a parametric model can achieve almost any form, many steps must but considered to achieve the same precise form in analog. The following steps articulate the process by which we achieved the translation from a parametric model to physical formwork for a series of prototype.

The Mix - The techniques and methods discussed pertain to the ability for new concrete technology to perform in ways not achievable 10 years ago. The concrete mix, with extremely fine aggregates, results in high performance concrete with high strength and lightweight density (1.4 kg/l in comparison to 2.4 kg/l for 'standard' concrete) to create much lighter and thinner forms. The high strength of the material (after 28 days 65 MPa/9500 psi) offers the ability for concrete to be thin and light enough to fold into position. In addition, the lightness of the concrete also reduces the dead load of the structure and therefore helps to reduce the outward thrust at the supports. Due to the high flexural strength and fast curing of the mix, a flat piece of formwork can easily be 'popped up,' folded or creased like a piece of paper during the curing process.

Parametric Geometry - The shell forms were generated in grasshopper with specific coordinates that control the various degrees of change in the forms. Depending on the type of fold or 'crease' in the form, specific parameters were exaggerated or diffused in the model, such as height, width, depth, scale, distance between edges, middle and corner points, or surface alignments. These parameters were then used in varying degrees of complexity or aggregation to produce different scales and proportions of the shell structures.

The Fabrication Process - Once the geometry in grasshopper is established, a final form is flattened into a pattern that is CNC milled as a series of flat elements for the formwork. To re-establish the formwork as a dynamic surface, similar to the grasshopper model, edges and points of the formwork are defined as either 'peaks' or 'valleys' to either be pulled up or pushed down in the fabrication process. In initial prototypes, the individual elements of the formwork are hinged together on either the front or back to create the peak or valley of the creased surface. Once the formwork is hinged and flat, it is ready for the concrete to be poured into position. After the concrete is poured into the flat formwork, during curing it can be 'popped' into the final position . Given the position of the hinges on either side of the formwork, similar to the computational model, the folds self-position when the outer points of the formwork are pulled up to define the overall geometry (Figure 2).

Dynamic Structural Aggregation - A singular formwork can produce a series of shell elements; resulting in an aggregated system of shells to form a larger structural framework. The intention with the formwork is to not only produce iterations

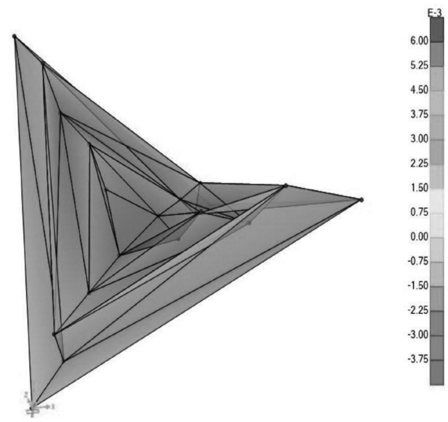

Figure 4: SAP2000 Structural Diagram and pulled up into the final shell form (Diagram by Author).

of forms but to generate a more dynamic structure where a series of elements can vary in height, width, or depth with a singular formwork.

The digital model also provides precise measurement of seams, edges, and boundaries so that the formwork can accurately be measured and concrete can precisely be poured into the formwork to generate the varied degrees of structural

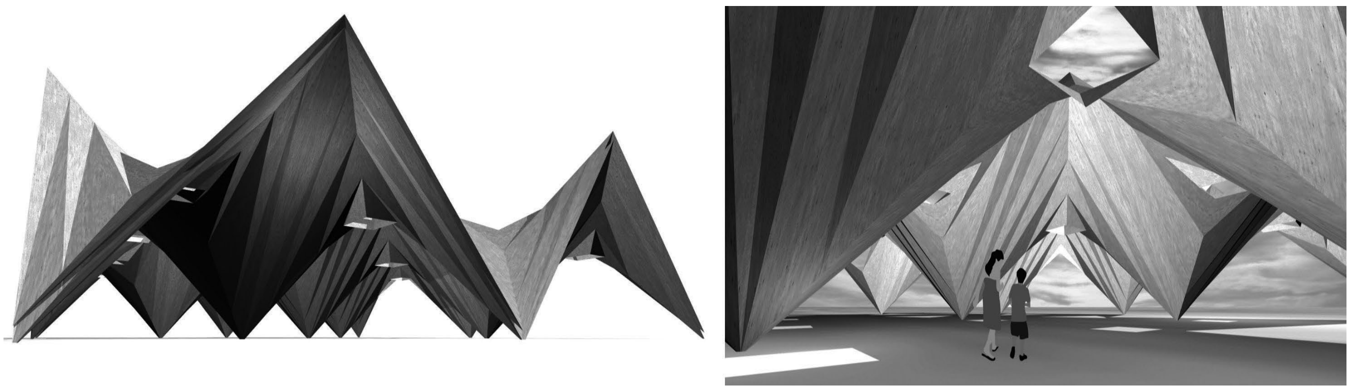

Figure 3. Spatial explorations of aggregated pop-up 'shells' (Rendering by Author).

forms. It is this play of formal generative logic that truly utilizes one simple formwork for a multitude of varied forms (Figure 3). This allows for a very rapid construction of complex geometries with minimal labor and drastically reduced weight and material.

Structural Analysis - The concrete shell was preliminarily tested in SAP2000 to check for overall stresses on the surface (Figure 4). The maximum principal stress (SMAX) on the visual surface under the self-weight is small enough for the current mix design, even with some stress concentrations in the middle area due to the overall compressed form and the individual creases in the middle of the surface. The even stress distribution implies that it is possible to evenly scale up the shell without disproportionate local increases in stresses.

RESULTS

The Pop-up techniques and prototypes (Figure 5) resulted in four fundamental observations.

First - The complex and messy relationship between digital form, mix and fabrication helps to recalibrate new fabrication strategies for computational form but also challenges the economies of labor, material flow, and production. The questions explored in this research project reflects how new fabrication techniques make it possible to reconnect with the tradition of shells as ubiquitous methods for roof construction that engineers/architects like Candela and Isler were able to popularize.

Second - Pop-Up Concrete is in the early stages but has already proven that the mix is viable for the pop-up formwork technique. The technique will become more feasible once the shell formwork increases in size. In the first attempts, the formwork was too small and became finicky to move into position. But as the size of the formwork elements increased, it was simpler to adjust the formwork with large hinges and wider gaps between elements; making the creases in the form capable of self-positioning with little friction.

Third - The first prototypes resulted in a concrete that could easily be molded into a complex geometry without slumping and result in a form that closely simulated the computational geometry. But progress needs to be made in terms of defining precise edges, corners and connections as more forms are made to aggregate and connect to one another. More details will be required to pre-cast voids in the concrete for pin connections to attach multiple shells together. In addition, a detail is in development to ensure a proper foundation that can resist the occurring outward thrust through the use of a tension member that spans between the supports. Ideally, this member could double up as a rail to move the formwork during the pop-up process .

Lastly - The computational goals of creating a singular formwork that can vary in height, width, and depth, needs to be carefully calibrated to ensure that edges of different shell structures can align without unwanted gaps between forms.

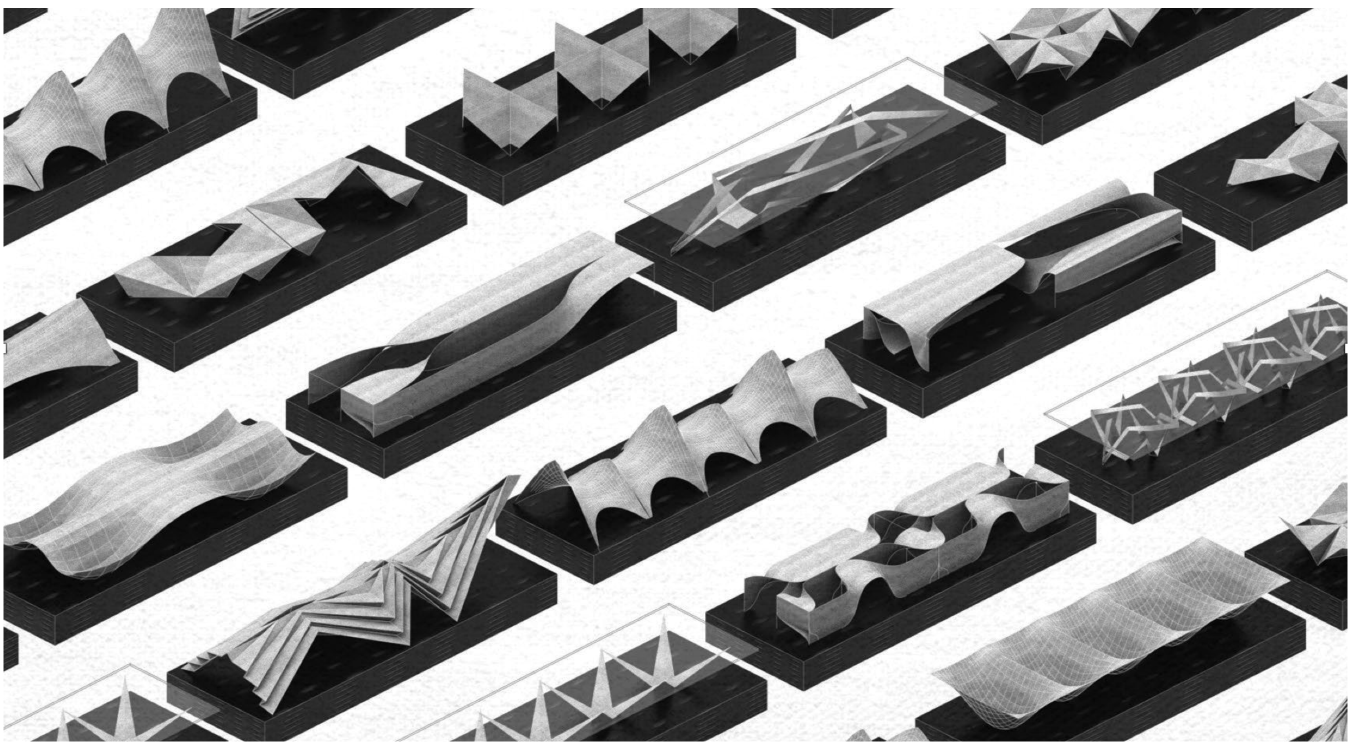

Figure 5: A new concrete playbook - formal speculations with pop-up technique based on program of bus shelter (Renderings by Author and Research Assistant John Mikesh).

CONCLUSION

Pop-Up techniques using lightweight, high-strength concrete has the potential to compete for building components, such as shell roof structures, that are quick to construct and use far less material for the formwork. If the construction process for concrete can become faster, simpler, and less expensive to deploy larger structural frameworks, there is potential to enter into markets where concrete is commonly overlooked.

The technique offers a variety of shell structures that were more ubiquitous in the 1950s and 1960s, such as factories, airplane hangers, train stations, bus terminals, etc. and can become a new application at the scale of repetitive prefabricated elements and singular structures. By rethinking the playbook of concrete and its formwork as heavy, massive, and complex to build towards materials and fabrications that are thin, light and flexible, 'pop-up' offers an opportunity for complex geometric concrete forms to become more proliferate; bringing shell and folded structures into the competitive field of mass-produced and mass-customized buildings.

ENDNOTES

1. Arup, Ove and Faber, Colin. 1963. Candela's work: Candela, *The Shell Builder* New York, Reinhold Pub. Corp., 194-198.
2. Chilton, John. 2000. Heinz Isler, London: Telford. 106
3. Billington, David and Garlock, Maria. 2008. "Thin-Shell Concrete Structures: The Master Builders." In *Seven Structural Engineers The Felix Candela Lectures*, edited G. Nordenson, The Museum of Modern Art, New York. 161.
4. Windeck, Georg. 2016. "Evolutionary Structural Optimization," In *Construction Matters*, Powerhouse Books, Brooklyn, NY. 80
5. Sasaki, Mutsurō and Isozaki, Arata and Itō, Toyo. 2007. *Morphogenesis of Flux Structure*. London: AA Publications, 87.
6. Culver, Ronald and Sarafian, Joseph. 2017. "Robotic Formwork in the MARS Pavilion: Towards The Creation Of Programmable Matter." ACADIA 2017 | *Disciplines + Disruption*, 522.
7. Veenendaal, Diederik, and Block, Philippe. 2014. "Design process for prototype concrete shells using a hybrid cable-net and fabric formwork". *Engineering Structures*. 75: 39-50.