

# Design, Analysis and Fabrication of Expressive, Efficient Shell Structures: A Prototype exploring synergy between architecture, engineering and manufacture

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## Abstract

The research-prototype is a 4 x 5 x 2m, "topologically optimized" concrete shell that was designed and built in ten days. The prototype and this ensuing paper aim to extend the rich legacy of form-finding to adequately represent the complexities of scale, digital design systems and delivery mechanisms of contemporary architectural practice. They explore synergies in early design between architecture, structural engineering, and manufacturing.

**Keywords:** conceptual design, form finding, topology optimization, concrete shell structures, computational design tools, structural design and analysis, CNC routing, digital fabrication, emergent economy

## 1. Introduction

Contemporary architectural design and construction, operates under extreme pressures of time and resource management. Design-development times are progressively being reduced while the complexity of spatial, structural and manufacturing parameters – are constantly increasing. Significantly, a majority of design decisions with regard to the overall geometry of the project are made within a compacted early-design phase. Subsequently, down-stream production and delivery processes post-rationalize such geometries whilst attempting to retain the design intentions from the early-phases. Such a process comes at a high premium of resources – time and personnel. Thus, there is increasingly a need to inform architectural design with critical aspects of structural design and fabrication processes from the early stages. This paper presents the specifics of one such time-bound collaboration, including: an examination of computational geometry and design tools and their use in a multi-stage, collaborative design phase, application of topology optimisation methods for design and form-finding of concrete shell structures; incorporation of structural design in early-design; and strategies to describe complex geometry (i.e. form-work and steel reinforcement layout) onsite in a labour intensive economy and the teaching thereof.

## 2. Computational geometry and design technologies

### 2.1. Subdivision surfaces

#### 2.1.1. Tacit Knowledge & iteration

The production of simulation - friendly geometries is not a novel or relatively unresolved process in itself, as digital simulation using particle-spring simulation frameworks is fairly well established especially following the work of early (architectural) exponents such as Axel Killian (Killian and Ochsendorf, 2005). However, this section describes the production of geometries that not only satisfy that criteria but also a number of others, such as fulfilling certain design intentions and the achieving of a desired structural performance.

This early design workflow stresses an intuitive and qualitative knowledge aided by feedback generated between early design methods and downstream validation processes such as structurally-based topology optimization and fabrication constraints. This feedback loop is improved by the utilization of rapid iteration and the evolution of the design geometry aided by the trial and error, volume dependant nature of information.

### 2.1.2. Designing for a convergence solution

Generating these resultant geometries leads to the requirement of managing expected high resolution, simulation-friendly meshes, met by working primarily through a proposed low resolution, designer-friendly (Shepherd P. and Richens P. [1] and Bhooshan S. and El Sayed M [2]) *Hierarchical Subdivision Surface* (HSS). This workflow generally begins with a designer's sketch solution to a spatial design problem, typically manifested as a pre-dominantly quad-faced, low resolution mesh. This mesh is constructed to accommodate design features such as topological conditions and directionality, holes and/ or boundary conditions, touchdown points, clearances, etc. Given that these morphological developments rely both on the iterative nature of the process and quick time-span of each iteration, ease, intuition and speed of manipulation become crucial. This makes the low resolution nature of the design mesh quite important, as it creates a freeform, manipulation friendly geometry used to explore design possibilities and limitations. A low resolution mesh also facilitates the intuitive tracking of important technical details such as the presence of singularity points and eventual pre simulation details, such as holes or fixed boundaries. This is possible due to the ability to manipulate the geometry's through adjusting a few vertices and/ or the addition/ subtraction of a few faces (Fig. 1)

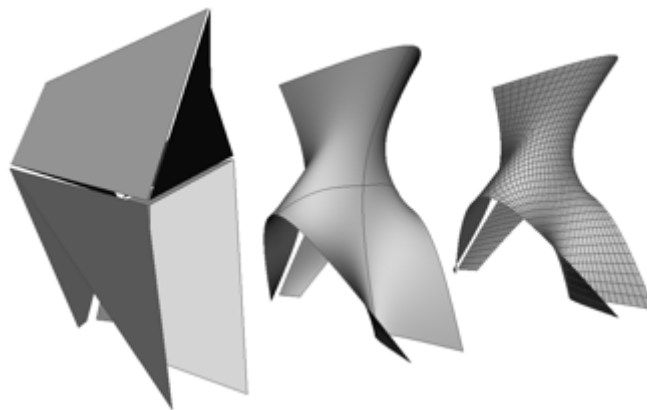


Figure 1: Multiple resolutions of design mesh, showing relatively low number of faces (6 faces) used to create complex surface.

Furthermore, by taking advantage of the recursive refinement structure of subdivision surfaces the low-resolution mesh is easily converted into a high-resolution mesh. This higher resolution mesh has nice attributes such as majority of its vertices of having equal valence, relatively even spacing of vertices etc. These features are beneficial for downstream processes as conversion to NURBS surfaces, even Finite Element Meshes etc.

### 2.1.3. Structural performance intuition

The manipulation friendly aspect of the workflow also allows for another major advantage, namely that of using a qualitative and intuitive understanding of structural principles of complex topologies to shape the base geometries. This is achieved primarily through two avenues, the first being the ability to describe relatively large curvature areas in the geometry's topology with a fairly small and easy to manage amount of geometric information, typically three to four mesh faces. The second is the aforementioned ability to control and influence

the presence of singularity points (Fig. 2) in the overall tessellation of the inherited high-resolution mesh. These are crucial as they usually describe points at which curvature inverts or drastically changes in the geometry. Such areas typically correlate with areas of weaker structural performance. These points are easy to spot and predict in the low-resolution mesh as they tend to occur when the mesh valence varies from the predominant quad-based subdivision, at a particular vertex.

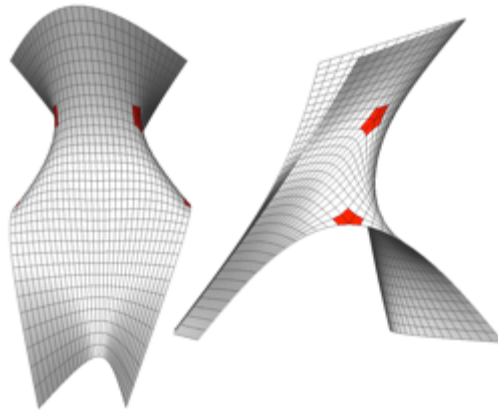


Figure 2: High-resolution mesh with highlighted singularity points

#### 2.1.4. Downstream benefits

A HSS based workflow as described, allows for the explorative evolution of multiple design resolutions through rapid iterative processes. This then, develops both an intuition for structural performance and also resultant geometries that are suited for downstream verification and analysis (as described previously). Additionally, the resultant geometries of the topology optimization processes (described in next section) needed to be rebuilt in a similar low-resolution manner. This is mainly due to the fact that the Finite Element mesh is subdivided to a resolution suited to the optimization process but neither conducive to other downstream processes nor design manipulation. The rebuilding process is aided by the discrete nature of describing a subdivision mesh through vertex placement and edge connections, which in this case was guided by the primary curvature lines of the optimized mesh. The benefits of the rebuilt mesh were most clearly observed in the structural analysis stage, where the mesh resolution and topology were easily edited to suit the process.



Figure 3: Left to Right : High resolution mesh FEM mesh ~50000 vertices ; multi-patch, medium resolution mesh ~6200 vertices ; low resolution, predominantly-quad, mesh ~ 275 vertices;

#### 2.2. Topology Optimization

The application of topological optimization (TO) as a constitutive design tool has obtained widespread adoption within aeronautic, automotive and naval industries (Bendsøe, M. P, and Sigmund O. [3]). While initial research on the application of TO to architectural structures indicate the possibility for both significant performance gains - in terms of reduction of material consumptions – and the infusion of particular design qualities specific to the process (DOMBERNOWSKY, P, and SØNDERGAARD, [4], DOMBERNOWSKY, P, and SØNDERGAARD, [5], STROMBERG, L. L. et al.[6]), the topic in its relation to architectural construction remains widely unexplored. The prototype presented in this paper explores a bi-directional, generative modus of design application, in which the result of topological optimization not only serves to reduce the self-weight of the concrete body through the generation of structurally efficient rib patterns, but also to significantly affect the appearance and effect of the final architectural object.

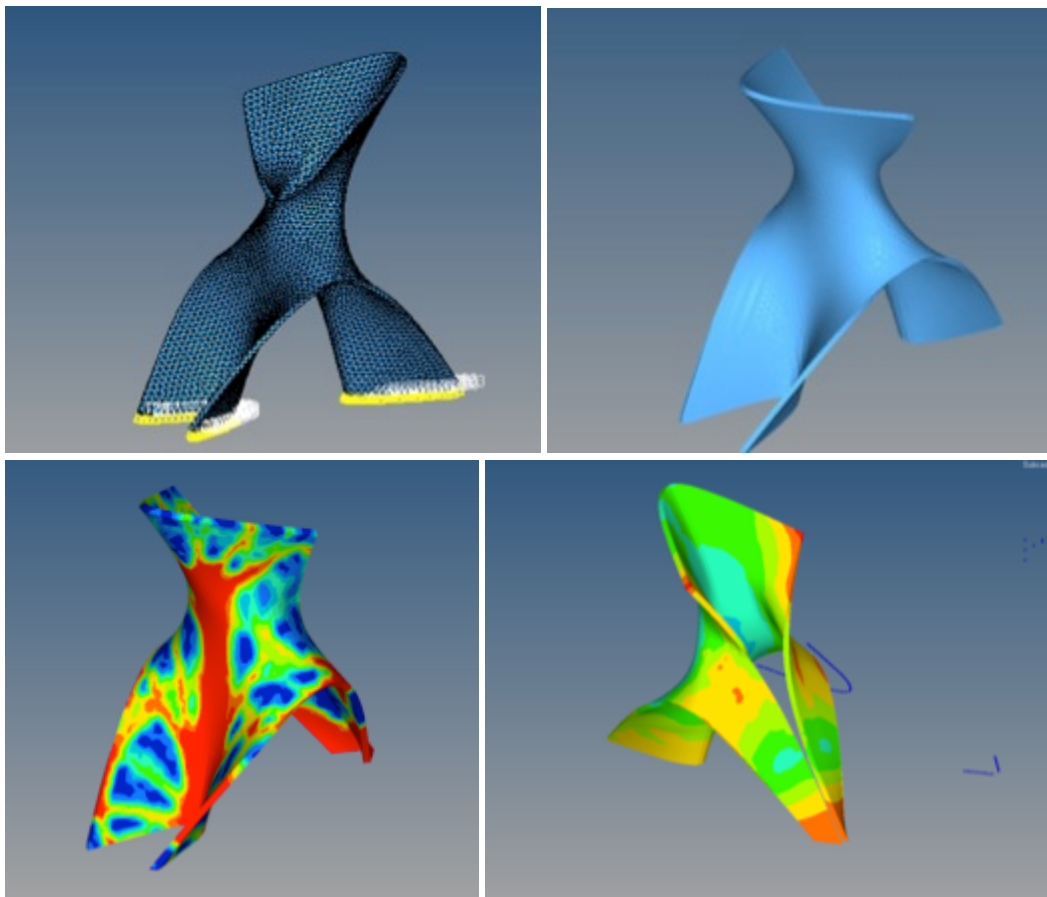


Figure 4: Shell design space FE model (top left), Shell design space FE model (top right), Material density distribution after topology optimization (bottom left), displacements of post-optimized concrete body (bottom right)

This was achieved through the following optimization process: the shell geometry, designed following the steps documented in the previous chapters, was approximated in the FE-solver, HyperMesh 11.0, to a tetrahedric Finite Element-mesh of 100 x 100x 100 mm units. Assuming a reinforced C35 concrete of  $6.5e+9$  elasticity module, a tensile strength of 3 MPa, and a compressive strength of 34 MPa, the mesh was subjected to a uniform load of 2.92 kN/m<sup>2</sup> on the outer surface in the  $-z$  direction – representing the dead load and wind load of the structure - and fully supported along the bottom shell edge. Using the optimization solver, Optistruct 11.0, this setup was topologically optimized for a minimization of compliance with a volume fraction of 25%.

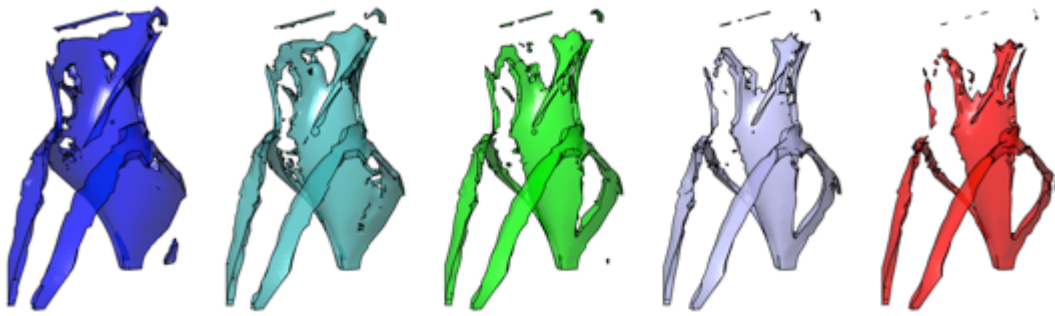


Figure 5: Optimization results density studies

The resulting topology, analysed in Hyperview 11.0, exhibited a 5.67 mm of displacement and maximum tensile stress value of 0.08 kN/cm<sup>2</sup>; well within the accepted properties of the material. Applying a density filtering of 0.29 the optimized mesh was re-exported and remodelled in the Rhinoceros 5.0 CAD-modeller. The post-processed interpretation of the optimization result held a volume of 1.219 m<sup>3</sup> by comparison to initiating starting volume of the original shell of 1.85 m<sup>3</sup>, representing a 34.1 % reduction of volume through optimization. Through this operation, the self-load of the concrete body was reduced, hereby rendering visible the principal load trajectory pattern of the structure as perforations of the input design space volume

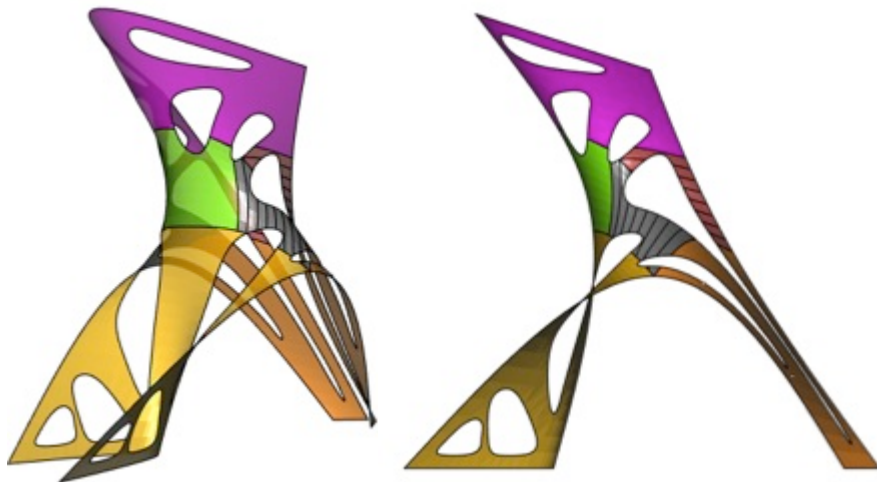


Figure 6: Remodelled geometry in McNeel Rhinoceros

### 3. Structural design

The structural context of the design and the envisaged methods of construction, required us to include various considerations and make appropriate responses in the structural engineering of the proposed design. This section describes them.

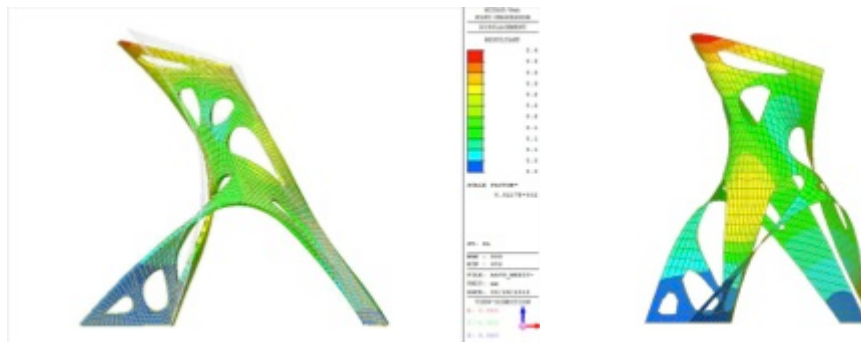


Figure 7: Deflection analysis

### 3.1 Governing lateral load : Seismic or wind loads.

Given that Mexico City is in a seismically active area, we had to consider whether to use seismic loads or wind loads as the governing lateral load. Following are the key assumptions we made, and subsequently decided to use seismic loads of 300gal as the governing one.

1. DL (Self-Load) =  $24\text{kN/m}^3 \times 0.08\text{m} = 1.92 \text{ kN/m}^2$
- 2a. EX (Seismic Load, 300gal) =  $\text{DL} \times 0.3 = 0.576 \text{ kN/m}^2$
- 2b. EX (Seismic Load, 200gal) =  $\text{DL} \times 0.2 = 0.384 \text{ kN/m}^2$
3. WX (Wind Load) =  $0.44 \text{ kN/m}^2$  (Based on the wind-code tables)

### 3.2 Foundation design.

#### 3.2.1 Stiff beam versus counter-weight approaches.

The above assumptions had a substantial impact on the design of the foundation. Given that we were attempting to amount of concrete used via TO, we were conscious not to lose those savings in the design of the foundation of the structure. This section describes the various considerations and the final choice of foundation design made. (Figure 8)

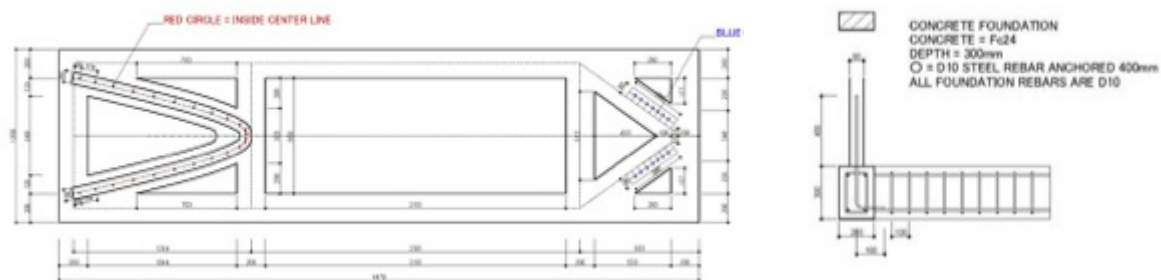


Figure 8: Foundation design as a stiff beam.

Under self-load, the reaction uplift, due to the geometry of the structure, were 200Kg (both sides) in the front leg and 60 Kg (both sides) at the rear. These could have easily been countered with the weight of foundation. However the foundations had to consider the lateral loads mentioned above. Under 300 gal lateral loads, the shell was found to be very sensitive against the side way (Y-axis) forces. We needed a foundation beam of about 20cm x 30cm rectangular section at both front and rear touchdown areas. Further, these foundations required that they have wider footings (40cm to 60cm width) to spread the overall weight evenly to the supporting ground. Additionally, the primary arcs of the touchdown areas of the geometry, come very close toward the front leg, allowing rather limited stance between each touchdown point to act against bending action. Thus, even though the overall weight was about 2 tonnes, the concentration of compression and tension at each touchdown point would have become about 5.5 ton. It would have been rather uneconomical to try to cancel this heavy tonnage

with counterweight of concrete. Instead, we thought of designing a foundation beam with sufficient stiffness and sectional area to act against the induced bending moment and shear.

### 3.2.2 Toppling.

Another issue to be considered was that of toppling given the tall and narrow proportions of the design. However, we found that the geometry was on the safe side given the following: i) Centre of Gravity, upon which the lateral force acts, is 1.78m from the ground, much lower than 3.0m ii) Weight of the shell is 23.5 kN, including the steel, and much lower than 30.0 kN. Considering the factors above, we decided to design the foundation as a stiff beam of 20cm x 30cm box with 40cm x 10cm footing for the front legs. The tail was supplied with the foundation beam of the same profile as the geometry. We then connected these two isolated foundations together by a pair of concrete beams on either side. Connecting beam was found not to require a footing. This foundation was estimated to weight about 0.5 ton, significantly less than the counter-weight strategy.

### 3.3 Bending moments.

Upon analysis, it was found that the highly curved geometry of the shape induced considerable bending action in the structure. The compressive stress values used for analyses, were reduced to the approximately  $2/3^{\text{rd}}$  the design strength of the concrete as concrete could fail at lower than its compressive stress due to such bending effects.

### 3.4 Distance of apertures from boundary.

The topological optimisation process produced long thin elements at the rear of the structure. These however, had to be reduced due to the possibility of buckling given the very small distance from the edge to the perforation. A minimum distance of 120mm from the edges was established all around the piece and not any concrete element was less than 120 x 120 mm in cross section.

### 3.5 Manual installation of steel bars.

Free-form nature of the geometry of the shell meant that the principal moment vector changed drastically across the shell. On the other hand, considering the practicality of manual installation, rebar placement would not be as flexible as we would need it to be. Therefore, we needed to make somewhat redundant rebar placement on both U and V directions of the shell, so that each can cover both upward bending and downward bending by themselves. Additionally, analyses performed after increasing safety factor to 5, to account for construction errors and concrete creeping, also indicated the prudence in this strategy. Lastly, 8mm diameter steel bars was specified, since at that thickness, it could be manually bent to conform to the geometry.

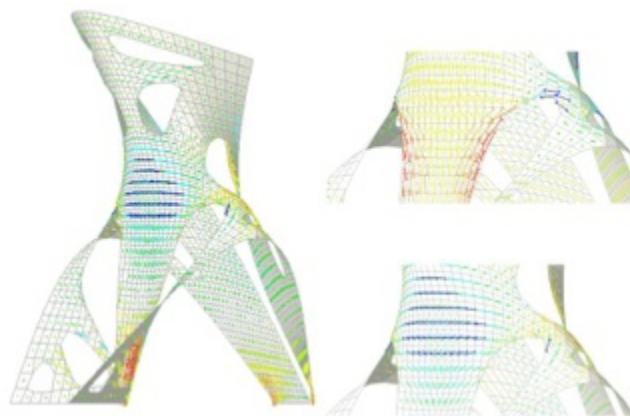


Figure 9: Principal moment vector field.

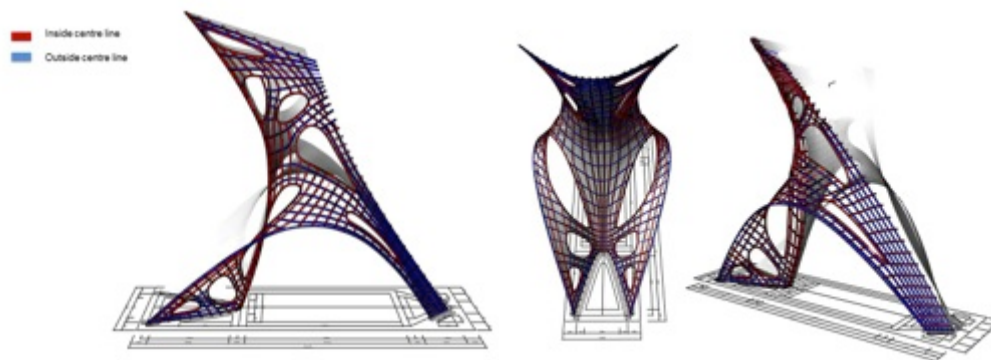


Figure 10: Reinforcement distribution diagram

#### 4. Fabrication

Following an iterative process of structural analysis and design refinement, the optimization result was remodelled in Rhinoceros for achieving a final topology optimized geometry that satisfied all the conditions of the seismically active environment of Mexico City and with the adequate size to be built in 10 days using manual labour. Given the complex geometry of the shell and the existence of a CNC router on site at the Tec de Monterrey we decided to contour the shape and cut it out of EPS Foam panels to be assembled on site and serve as a guide for the workers to layout the rebar and pour the concrete. An inverted negative of the shape was remodelled on Rhino establishing all the edges at 90 degrees normal to the original surface to avoid the need of perimeter tubes and be able to create a continuous curvature on the edges (Figure 11). This model was divided in 12 pieces that could fit the bed of the CNC machine and contoured at one-inch segments, an interval that corresponds to the thickness of the low density polystyrene sheets that were locally available; subsequently the contours were nested to achieve the maximum material efficiency while reducing the cutting time. As the model is symmetrical in one axis it allows us to cut some pieces of foam together and then rotate them 180 degrees to get their final position (Figure 12). The contours were glued utilizing polystyrene solvent free industrial adhesive on 12 blocks of contour, to allow them to be transported on site; utilizing a contour approach to the shape generated another layer of texture to the geometry, accentuating the curvature of the shell.

##### 4.1. Construction on the building site

Once on site the construction of the formwork was organised in 12 blocks of contours, of in all 160 polystyrene sheets. External scaffolding towers were deployed on site comprised of standard 2000 x 600 mm modules to allow the workers to walk and move around the prototype (Figure 13). The formwork was only going to be utilised as guide work for the workers on site so it didn't need to be sanded to reduce the texture of the contours or coated with any releasing agents. The polystyrene blocks were assembled and reinforcement bars placed by hand following the curvature of the surface. A double sided wire mesh slip was created around all of the perforations of the piece to ensure geometric fidelity as the rebar proved to be difficult to bend on this closed angles accurately and using thinner wire would not strong enough to receive the concrete (Figure 14). After placing the reinforcement bars a double layer of wire metal mesh was applied on both sides of the rebar to receive the concrete mixture. The edges of the piece as well as the perimeter edge of each of the perforations had to be covered with a double layer of wire mesh enclosed in a slip of plastic to ensure that the concrete mix remains perpendicular to the surface all around the edges, as doing a perpendicular edge in a traditional manner would have been extremely complex given the curvature of the piece.

A low water concrete mixture was cast into this double layer of metal mesh; to avoid the need of vibration the concrete was poured and compacted in 4 step sequence –back bottom areas, front bottom areas, middle and top - the foam guide work had to be removed immediately after casting to be able to take it out without damaging the surface and without having to destroy or further cut it.



A layer of high water cement paste was applied to the piece after finishing the cast to even the surface and prepare it to receive subsequent painting treatment. The prototype is in a public park in the Santa Fe area of Mexico City and was opened to the public on the 20<sup>th</sup> of September.

The process from 3d modelling and preparation of formwork files to on-site casting took 10 days and the concrete was left to cure for 2 more weeks.

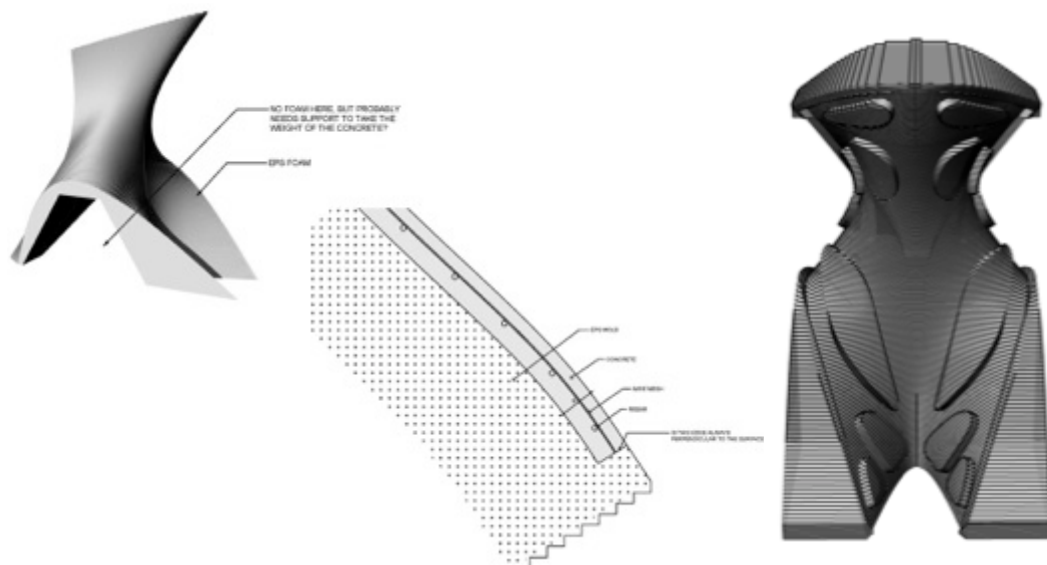


Figure 21: Typical section of the formwork guide (left) and contoured negative model of the geometry (right)

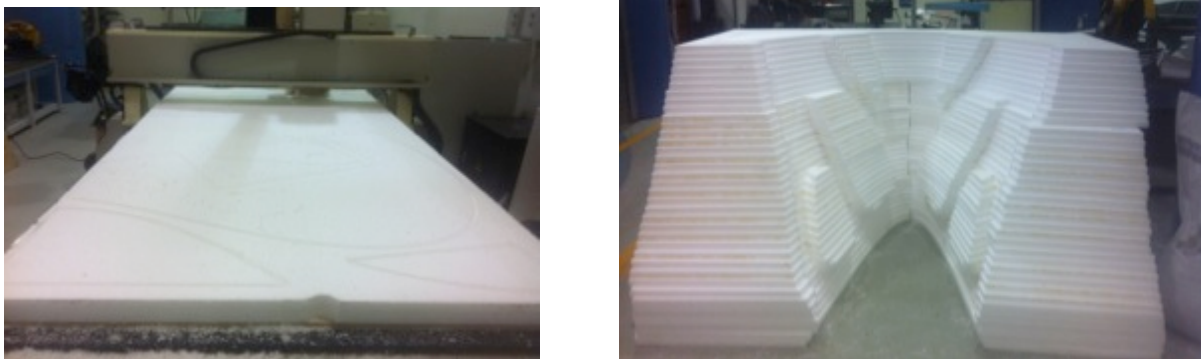


Figure 12: CNC routing of contours (left) and contours ready to be glued and transported on site (right)



Figure 13: On site assembly of the formwork with scaffolding towers to the sides and placing of the reinforcement bars



Figure 14: (left to right) Perimeter edges cover with reinforced wire plastic slip. Piece after concrete was poured and formwork removed.



Figure 15: Topology optimized shell prototype 4 x 5 x 2m, 8 cm thick

## 5. CONCLUSIONS

We presented the specifics of a time-bound design collaboration, including *computational geometry and design tools* and their use in multi-stage collaborative design phase, incorporation of *structural design* in early-design, strategies to *describe complex geometry* – form-work and steel layout – onsite in a labour intensive economy.

### 5.1 Computational geometry and design technologies.

#### 5.1.1 Subdivision surfaces

Growth in the role of simulation in conceptual design and evaluation of building performance is coupled with need for architects to manage the dichotomy between high resolution geometries used in simulation and lower resolution, free-form manipulation friendly, CAD geometries. We argued for the benefits of *Hierarchical Subdivision surfaces* in this process, concentrating specifically on its uses in:

- i. Design and collaboration workflow, enabling multiple resolutions of design and analysis, rapid iteration and evolution of design geometry.
- ii. Developing an intuition for structural performance of geometries due to the nature of the smooth curvature flows produced by subdivision geometries and the correlation of the curvature with structural performance.

#### 5.1.2 Topology optimisation and shell structures.

Incorporation of structural analysis within the rapid, iterative and free-form nature of early design is quite a challenge. The methods and software are neither easily accessible to architects nor easily incorporated within methods and software they use. Further they are time-consuming and defy easy integration of architectural constraints. In this context, recent developments with regard to development and availability software to

optimise material layout within a given design space is a welcome development. We specially argued for the benefits of such *topology optimisation* in:

- i. Reduction in material quantities, and thus reduction of economic and environmental costs.
- ii. Reduction in the design iteration time.

## 5.2 Structural design

We also discussed the difficulties in developing details of structural design in the context of free-form geometry, seismically-active physical environment and labour-intensive economic environment in which the prototype was built, focussing specifically on:

- i. Development of reinforcement fibre layout in the geometries developed by the processes above.
- ii. Design of foundation for such unusual geometries, with the explicitly design intention to minimise the size and complexity of the same.

## 5.3 Fabrication.

Further we presented our strategies to enable a straight-forward translation of the design to physical reality including:

- i. Description of geometry complex geometry on-site, given the constraints of time and labour intensive economy.
- ii. Development of guide-work / Form-work for concrete negotiating requirements of pouring/compaction with the complexities of the geometries produced by *topology optimisation*.

In conclusion, we hope to have made a case for a more holistic design practise – from collaborative design to fabrication, and a thus a more holistic reduction of costs – design time and resource, material savings via topology optimisation and the need to include fabrication costs in such evaluations.

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