Performance driven self-supporting curved surface morphologies and tectonic in current practice

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Advances in the computational simulation techniques in the last decade have prompted increased interests and emphasis to be brought onto performance driven design approaches. As a result, tectonic, describing the relationship between structural and architectural properties has become one of the main topics in the discourse related to form finding methods in digital design. This paper specifically highlights the computational tools, workflow and research agenda pursued at Zaha Hadid Architects. The selected projects in this paper showcase how structural performance, fabrication performance, and material intelligence inform the resulting morphologies through computational design in different architectural scales and the technologies employed to realize complex morphologies. Self-supporting curved surface such as shell structures are provided as examples of multi-performative morphologies which integrate structure, skin enclosure, material, fabrication, spatial and social function through topological variations. This paper aims to illustrate research driven form finding and fabrication methods that are interdisciplinary in nature and the computational methodology to integrate bottom up design process in current architectural practice within the constraints of real-world construction industry.

Keywords: tectonic, simulation driven design, performance driven design, digital fabrication, material properties, tessellation, multi-performance morphology, design to production pipe line, interdisciplinary design process

1. Introduction

This paper elaborates on the effort made by Zaha Hadid Architects (ZHA) with a research driven design approach to consider architectural design, performance simulation and fabrication as an integral process. This design thinking in ZHA is in effort to bring architectural design and engineering closer together in synergy during the design process, and this is highlighted in the exploration of the concept of tectonics.

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In recent years, the concept of digital tectonics has been proposed as a shift in design thinking to combine architectural, structural and material design through computationally controlled processes. Due to the advances in simulation and algorithmic approaches, it has also been linked to the notion of digital morphogenesis (Oxman, 2009). To reflect this design thinking, various researches have been linking parametric models, computational simulation tools and search algorithms (Lachauer and Block, 2014). Tectonic articulation of performative geometries is thought to be capable of integrating structural and fabrication intelligence. The idea of tectonics explored in ZHA's projects describes an underlying design thinking established by Patrik Schumacher, director of ZHA. In the works of ZHA, tectonics is addressed considering not only morphologies and computational processes, but also the design to fabrication pipe line, professional collaborations in construction industry, and fabrication methods that lead to the realization of projects. Schumacher differentiates the roles of architect and engineers by distinguishing built environment's technical performances and social performances which architecture is solely responsible for. He defines *Tectonic articulation* as the combination and expression of the two (Schumacher, 2014). This design theory together with computational design methodologies influences the morphologies of the projects described in this paper.

Tectonic articulation is most visible through self-supporting curve surfaces. Self-supporting curved surfaces present an opportunity to integrate architectural design concerns together with engineering and fabrication logic. When designing self-supporting curved surface structures, it is difficult to prioritize amongst the spatial logic of the volume, manifested form, material and structural logic. Thus, bringing the two disciplines of architecture and engineering closer during the design process. Shell type structures are one of the most well-known examples of structural surfaces. A research on form finding with shell structures can be traced back to the works of Gaudi and Frei Otto. Despite the seminal researches in shell structures and form finding methods, the redundancy in the construction process for building a shell type structure, the dual process of making the formwork and the structure itself, rendered it inefficient in the past in terms of cost, time and fabrication in comparison to other types of structure that are more efficient in the building scale construction. However, there is a renewed interest in shell as a self-supporting surface structure partially due to its tectonic articulation and the performance driven nature that it implies. The design research on shell structure at ZHA addresses the fabrication constraints of the shell by exploring the construction methods such as using fabric formwork and folded sheets to construct structural surfaces together with computational form finding methods (Bhooshan and El Sayed, 2012).

This paper describes the polygon modelling techniques specific to the workflow of ZHA and computational methodology and customized tools developed by the in-house computational design research group, CODE. The projects included in this paper vary from small furniture scale to architectural building scales. The small scale projects, 3D Print Chair Prototype and Shell Prototype, were carried out specifically for research purposes and they showcase researches in form finding process in shells which considers structural logic together with fabrication methods. Therefore the smaller scale projects described in this paper adhere to the pure structural and engineering logics of shell structures. Building scale examples are self-supporting surface designs which initiated from the concept of shell structure. This paper also elaborated on the potential of shell inspired self-supporting surface structures in the large scale construction considering multiple architectural criteria as form finding factors. It also elaborates on the limitations on current construction methods in a large scale structural skin and illustrates how the construction of Dongdaemun Design Plaza have benefited from the fabrication technique together with material intelligence in the construction of self-supporting surface with complex geometry. Shell morphologies described in this paper are considered to be multi-performative by integrating architectural, material, fabrication intelligence in form finding.

2. Theoretical Background and Design Technologies

Generally, form finding process is defined in relation to a structural behavior and it implies a process of finding a shape that can withstand specific gravity, compression or tension load. Different from this pure engineering point of view, the term form-finding in design process at ZHA implies a process of gradual development of the form based on performance criteria such as structure, environment, material or spatial related functions. This performance driven form-finding approach is facilitated by simulation driven computational methods to integrate performance criteria as informing factors in shaping the design. This chapter elaborates on the design potentials that self-supporting curved surface morphologies possess and provides a brief summary of the theoretical background of the polygon modeling technique and the particle spring simulation used in the form finding process of the shell morphologies.

2.1. Design Potentials of Self-supporting curved surfaces, Shell Structures

Shell structure is one of the most well-known curved structural surfaces. However, there isn’t a unified or a singular definition for Shell type structure. Instead, it is identified through characteristics. These identifying traits include curve surfaces and surface structures that are very thin in the direction perpendicular to the surface. With its broad definition of shell structure, the examples of shell can include masonry vaults and domes and common objects such as monocoque car body or glasses cases (Williams, 2011). The global geometry which is defined by the membrane of the shell and the structural properties are anisotropic in nature. Therefore, it forms a close relationship between the form, structural integrity and material (Addis, 45). The form finding process of a shell considers loads, boundary conditions and material layouts. With computational optimization, topological variations of shell morphology present vast design space and search algorithm is often employed to find a design solution suitable for the objective (Adriaenssens, 2).

Schumacher elaborates further on the potential of the shell structure with architectural objectives. He points out the organizational complexity that can be achieved with unified but hierarchical articulation of form through topological variations while adhering to morphological coherence. He describes that this logic and rule driven design approach and morphological studies can induce spatial arrangement, spatial recognition, and programmatic integration for the users. He also points out the possibility to integrate not only the structural performance in informing the geometry but also the sub-articulation such as ribs, perforation and tessellations as integral part of the governing design logic, providing an encompassing view of design as correlated systems (Schumacher, 2014).

2.2. Polygon modeling techniques in architectural design

Starting from the development of early obscure graphic-related projects from 1960s, more than a hundred thousand engineers and software developers have emerged from computer graphics community (McCracken, 1997). This facilitated the influence of computer graphics industry in computer-aided design and manufacturing due to the growing availability of graphical tools and systems. The visualization technologies present in the works of graphics oriented industry such as Pixar have influenced other industries such as automotive and aerospace, molecular modeling, medical imaging, and entertainment. Rooted from these historically interwoven relationships, architectural design industry also has been vastly influenced by animation techniques.

Techniques developed for 3D computer graphics has influenced Deconstructivist architectural movement during 1980s. Practices such as Gehry Technology, Coop Himmelblau and Zaha Hadid Architects pioneered in this exploration over the last 20 years to introduce advanced 3D computer graphics technology into architectural design and manufacturing process. At ZHA, the introduction of polygon modeling techniques in the conceptual design processes, has allowed the practice to be able to deliver geometries in architecture that are identified with higher degree of complexity and curvilinearity.

Rooted in the computer graphics industry, polygon mesh representation is based on a visualization algorithm which approximates their surfaces using simple polygon faces. Polygon with low resolution (low-poly) serves as a base mesh which can be subdivided further. In other words, complex shape with smooth and curvilinear surfaces can be described by a very simpler polygon addressed as low-poly. This low-poly mesh can be easily translated into different representation methods such as higher resolution polygon mesh, subdivision surfaces or NURBS surfaces. These base factors provide designers a greater flexibility in creating complex shapes using polygon modeling techniques. Due to the fast, easy and malleable nature of the subdivision surface modeling, the interactive shape modeling allows for integration of structure and fabrication constrains (Pottmann, 2014). This design method is especially beneficial for the designers by allowing them to explore the formal and structural relationships in the early stages of design through iterative processes. These advantages in ease of modeling and speed are more apparent in quad-faced low-poly models used in the form finding process and procedural modeling developed by CODE.

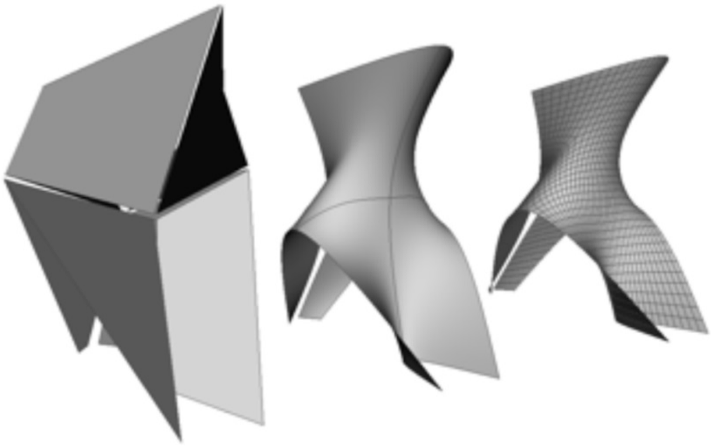

Figure 1. Low poly modeling

2.3. Form finding

The form finding process of the shell case study projects described in the later chapter uses dynamic mesh relaxation simulation (Day, 1965 and Barnes, 1999) based on a particle spring system. The particle spring system has an easy iterative ability that is beneficial for form finding process where modification of form happens repetitively. A particle spring system is made up of particles (points) that are thought to be the concentration of mass which is typically the self-weight and springs that connect these particles. During the form finding process, the particles oscillate until the system reaches equilibrium (Witkin, 1997). The physical parallel of particle spring system can be traced back to the works of Gaudi and Heinz Isler. Recently these principles have been adopted in computational simulation tools and are readily available for architects and engineers. At ZHA, this particle spring systems have been adopted to suit the digital work flow of the practice which is combined with low poly mesh modeling technique suitable for creating complex geometry (Shepher and Richen, 2009, Bhooshan and El Sayed, 2014,).

The implementation of form finding techniques developed by CODE has a long standing research background in computation in the works of A. S. Day for Dynamic Relaxation as well as Axel Killian's work in particle-spring simulation which can be considered as a translation of hanging chain model by Antoni Gaudi (Bhooshan and El

Sayed, 2011). However, considering the complexity of form displayed in the design of ZHA, the differences between the researches of others and the one of CODE have been their emphasis on establishing the efficient workflow between conceptual design and downstream delivery within practical constraints to provide immediate solutions to the on-site designers and engineers on daily bases (Bhooshan and El Sayed, 2011).

3. Design Methodologies

One of the main concerns in commercial practices regarding design methodologies and workflows is the relatively quick time-span of design iterations. Therefore, one of the primary objectives when considering the computational workflow is to develop tools and procedures suitable for the complexity of the architectural design to assist the design process within the given time and economic constraints. Zaha Hadid Architects has been designing a greater part of their projects using polygon modelling techniques during their conceptual stages due to the empirical design to production pipe-lines developed by the practice over the last decades. Thus, naturally, a large part of the customized computational tools and frameworks developed by the computational research unit at ZHA, CODE, are in the same paradigm. Based on the workflow within the office, a large part of the research carried out by CODE has been focused on establishing the design workflow based on low-poly surface modeling techniques and subsequent form-finding procedures, some of which are tested on the study of performative shell structures. The methodology and computational workflow described in this chapter specifically outline the procedures of the form finding process of shell morphologies based on low-poly modeling. The key benefits of this process are its ease of use, intuitive manipulation of geometry and speed of manipulation. This process illustrates how the computational workflow is established for speed, quality and accuracy of design iterations for simulation driven form finding.

The main workflow starts with the setting up of the initial low-poly model which describes the topological conditions such as touch down points, clearance, boundary conditions. Then the low-poly mesh is sub-divided into high resolution polygon mesh (high poly) using Catmull Clark recursive subdivision algorithm. This process can be done using the built in smooth-mesh function of Autodesk Maya. During this process, the numeric information of the low-poly mesh is stored in order to track back the high-poly after the deformation is made by the mesh relaxation simulation. The dynamic mesh relaxation simulation is carried out on the high poly mesh using customized tools developed by CODE based on particle spring system which enables the form finding process to occur under a given set of forces. The simulation process carried out on the mesh model perturbs points to satisfy fabrication and structural constraints as form finding procedure. After the initial form finding simulation, the additional step of analyzing stress direction using rain-flow analogy can be employed. This process analyzes the structural properties to approximate the flow of physical load. For example, the “rain-flow analogy” can be used in this stage in order to get results using a fast computational solution (Bogart, 2005). Additional structural analysis and optimisation based on finite element methods can also be carried out. A topology optimization process can be run to iteratively erode the shell surface to arrive at a perforated shell. The data generated from the simulation then can be used to create output according to different design intent or functional criteria. The post-simulation process follows the steps of procedural geometry generation, manual edit, exporting to down-stream applications. The design outcome is then delivered to engineers and fabricators. Downstream deliverables as well as the design-to-physical manifestations are also considered as a very important part of this design to production pipe-line.

4. Shell Case Studies

Each project in the following chapters emphasizes different aspect of the multi-performative morphologies. These projects elaborate on form finding, evaluation process and construction process of self-supporting curved surface morphologies.

4.1. 3D Print chair prototype

4.1.1 Additive manufacturing

The 3D print chair prototype (Figure 2) was produced in 2014 as a part of the research project on shell morphologies carried out by CODE. This prototype was produced as collaboration between ZHA and 3d printing company, Stratasys. 3D print rapid prototyping, also known as additive manufacturing, has gained its popularities due to the recent development and commercial availability and is now used widely in various disciplines. This advance in 3d printing technology led to a new paradigm in design and fabrication, opening up greater possibilities in innovative design. Notably, 3D printing narrowed the gap between digital design and its manifested physical products by considerably simplifying the production procedure, allowing objects with complex geometry to be produced. However, the most significant impact of introducing this technology in design to fabrication pipe line is in its new materiality which opens up a new paradigm in tectonics relations of material, structure and form. This 3D print chair prototype illustrates an innovative design project with in-depth understanding of technology and new materiality. This project utilizes the benefits of 3D printing techniques to create tensile structure. Additionally distributing different densities, porosity and varying degree of softness in material within a single printing process.

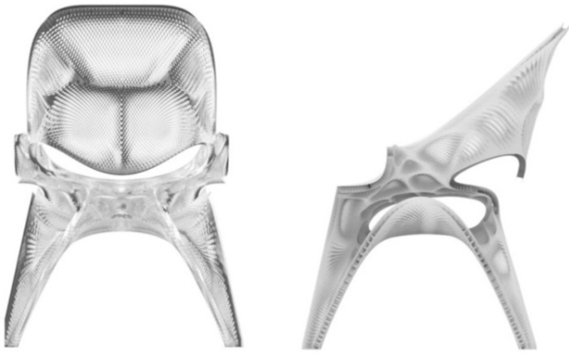

Figure 2. 3D print Chair Prototype Design

4.1.2 The design process

As an overall process, the design of the chair involved dynamic mesh relaxation of the global geometry which was followed by the topological optimization using structural simulation, Altair OptiStruct. This process allowed for the generated structural paths and perforations to simultaneously manifest a structural optimum and an aesthetic assertion.

As the first step of the design process, the base form of the chair was designed using low-poly modeling technique in Autodesk Maya. This initial geometry was converted into high- resolution mesh to perform dynamic mesh relaxation simulation using built-in NCloth Simulation within Maya (Bhooshan and El Sayed 2011). Relaxation of the mesh allowed the designed surface to perform as tensile structure and also the simulation resulted in a discretized polygon model with evenly distributed quads for subsequent structural simulation. Through this process the initial low poly model was developed into surface like geometries to frame large area of the chair surfaces to perform as tensile structure.

Structural simulation was performed on the resultant tensile-like surface for topological optimization to achieve material reduction and to identify areas where non-structural, low-density, soft material can be allocated. The structural analysis was carried out on high resolution mesh to calculate the load bearing areas using finite element solver, HyperMesh. Load of a person was applied to the seated area and the back support of the chair and the edges of the chairs were considered as boundary conditions for the simulation process. Based on the result of the structural simulation the mesh had to be reconstructed to follow the direction of the structural load. Then the data returned from the structural simulation was utilized in the subsequent stage to further develop the design considering the material distribution in the structural and non-structural part of the chair.

The depth of the structural surface of the chair was varied according to the result of the structural analysis, where red indicated the load bearing areas and blue indicated non-structural part of the surface (Figure 3). Based on the analysis, the more material was allocated along the structural loads. To further reduce the material in the non-load bearing parts of the chair, various sizes of the perforations were applied in non-load bearing areas. The range of sizes, initial shapes and the topographic distribution of the perforations were decided by design criteria. The final result achieved approximately 30-35 % reduction in material compare to the initial geometry before the topological optimization and the thickness varied approximately 3.5 times between structural and non-structural parts.

The design intention and the structural optimization processes accounted for varying degrees of density in material as well as softness of material. The non-structural parts, due to the object being a chair, were intended to be printed with lower density, soft material. The color and opacity used for the chair prototype represented the different degree of softness and density of the 3D print materials. At the time of the fabrication, there are no commercially available 3D printers which can print an object with varying density and materials in furniture scale while assigning a gradient of color according to the density of the material. Due to this reason the chair remains as a prototype and the color gradient of this chair remains as the representation of different materiality.

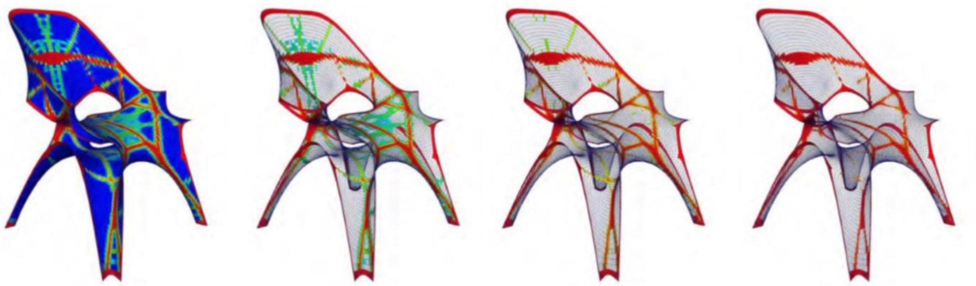

Figure 3. Result of Topology Optimization: Density Gradient

Figure 4. Photographs of 3D printed chair

4.2. Shell Prototypes

4.2.1 Design to fabrication production pipe line

The following projects describe the construction of shell structures in two separate locations, India and Mexico. These constructions took place in 2011 as a test bed scenario for contemporary design to production pipe line as part of design research carried out by CODE. These projects were done in collaboration with Alicia Nahmad Vazquez, Knut Brunier, and Joshua Zabel in Mexico, and with Chikara Inamura, John Klein, Abhiskek Bij, B.S. Bhooshan and Yadu Nandan in India. In both cases, the duration of the construction was limited to two weeks. The shell structures shared similar form finding process and were designed as minimal surfaces. The fabrication method relied on locally available construction skills and therefore the shells were built using ferrocement, traditional concrete construction with steel reinforcement wire mesh. Thus the structural system of the shells was comprised of concrete membrane diaphragms with steel pipes spanning the edges of the shells. However, different construction methods were employed in the two locations due to the available skill sets in producing the form work. Design and the structural simulation process considered the fabrication process from early on which influenced the overall global geometry. This paper highlights the form finding process and how the different fabrication process affected the realization of the shell morphologies.



Figure 5 (Left). Shell Prototypes construction in concrete
Figure 6(Middle). Waffle formwork in Mexico
Figure 7(Right) Fabric formwork in India

4.2.2 Form finding

The global geometries of the shells resulted in complex shapes which consider the structural performance, fabrication methods, material and architectural qualities. The development of the global geometry relied on real time simulation to give feed-back on the refinement of the form according to structural, construction and architectural needs. As an overall form finding process, more accurate structural simulation based on Finite Element Methods was carried out intermittently to confirm the form finding process based on particle sprint system (Bhooshan, Veenendaal and

Block) and the structural integrity of the final geometry was confirmed by the engineers prior to the construction.

The geometrical construction of the shells relied on quad-faced low resolution mesh which was then further developed into high resolution mesh with recursive subdivision, Catmull Clark Algorithm using built in function in Maya. The initial mesh model was developed to describe the topological conditions which included boundary conditions, touch down points and openings on the surface. The global geometry was subdivided into multiple patches prior to structural simulation to incorporate the construction of the edge pipes which were necessary for the structural stability. In order to bend the edge pipes with given construction methods, it was essential to obtain single curvature for the edge conditions. By sub-dividing the global geometry prior to the simulation it was feasible to obtain single curvature along the seams and therefore the subdivided patches were considered independently, resulting in series of minimal surfaces. Customized built-in Cloth simulator based on particle spring system was used in Autodesk Maya for mesh relaxation of the minimal surfaces prior to the structural simulation. The seams of surface patches were considered as fixed edges to minimize the deviation during the structural simulation. Due to the subdivision of the surfaces prior to the simulation, the resultant morphology has visible crease effect.

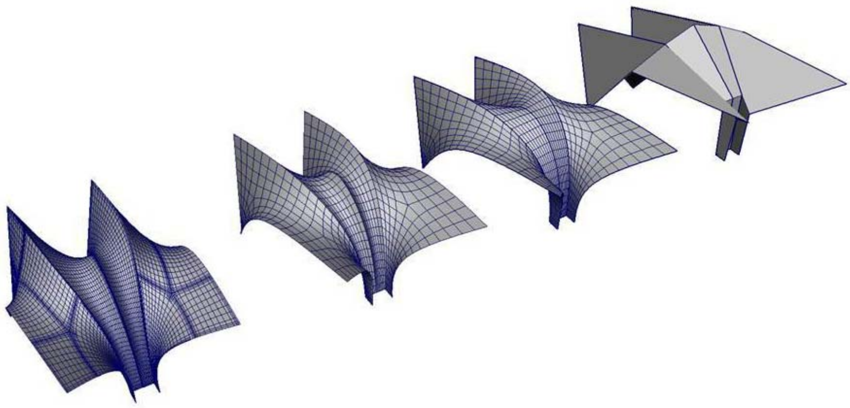

Figure 8. Low poly model and subdivision of shell geometry

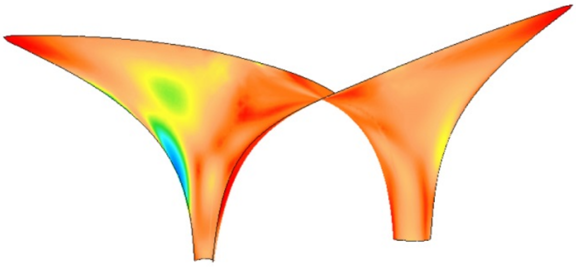

Figure 9. Simulation: Areas of tension, compression and defection

4.2.3 Formwork

As mentioned previously, the construction process relied on the available local construction skills which lead to the construction of fabric form work in India (Figure 7) and waffle system in Mexico (Figure 6) considering the time and cost constraints. In both construction methods, it was necessary to subdivide the resultant form for fabrication of formworks as post-simulation process. The recursive subdivision of the initial form allowed the properties of parent geometry, the result of the simulation, to be maintained in the subdivision process. The subdivided patches were then converted into 2d patterns using custom variations of in-built functions in Rhino to produce the formwork while minimizing the material waste. The formworks were assembled before laying out the reinforcement steel bar and hand rendered-concrete was applied as the final finish. It was noted by the participants that the more malleable construction methods using fabric formwork had the capability to correct the discrepancies in the digital model and computational simulation on site. Also, there was a paralleled relationship between the actual construction process and digital form finding process relying on the particle spring methods and the cloth simulator. The waffle construction was the direct translation of the digital form using CNC routers for fabrication. Due to the lack of malleability in the material and the construction methods, the discrepancies in the digital model were harder to rectify. However, it showed and advantage during the assembly of different structural parts due to reduced tolerance.

4.2.4 Further Development

Second shell structure was constructed in Mexico in 2014 as a continuation of the previous design research by ZHA CODE in collaboration with Alicia Nahmad Vazquez, Asbjorn Sondergaard, Chikara Inamura, and Joshua Zabel. Additional step of topological optimization process were employed in form finding for this project after the mesh relaxation. The structural optimization process was carried out using

Finite Element solver, HyperMesh and optimization solver, Optistruct 11.0 due to its fast simulation time. Based on the structural simulation, design process was introduced to allocate openings on the surface to reduce the material. The overall process mapped the paths of the structural load to reduce material considering dead load and wind load on the structure resulting in porous surface as a final morphology.

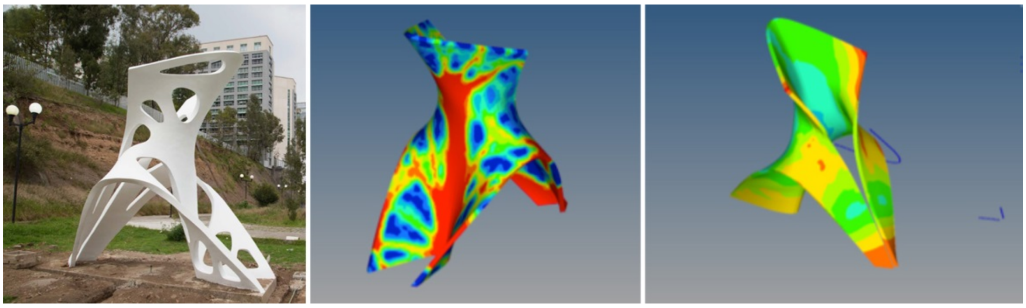

Figure 10 (Left). Shell Prototypes construction in concrete
Figure 11 (Middle). Material density distribution after topology optimization
Figure 12 (Right) Displacements of post-optimized concrete body

4.3. Application of shell design principles in building scale structure

4.3.1 General Design Approach and Construction Limitation

As an ongoing design research in ZHA, shells and shell inspired self-supporting curved surface based forms have been explored in multiple projects in architectural scale. When constructing the self-supporting curved surfaces in a large scale, the two main challenges are the integration of the multiple criteria during the form-finding process and finding the construction technique which can enable the complexity of the form-found morphologies to be realized within a given budget.

For large scale projects, aforementioned computational form finding process based on polygon modeling in the previous chapter are also employed in the design process. However, different from the previously mentioned pavilion and furniture scale projects which have benefitted from research focused approach and seamless workflow from design to fabrication, in the architectural scale projects, often the fabrication technique is not known to the designers during the early design stages. Therefore, information regarding fabrication when dealing with bespoke elements with complex geometry is not commonly integrated in the form finding process in the early design phases due to the established design development stages and procurement process in the practice.

The projects also need to consider additional criteria suitable for the complexity of the programmatic requirements. Functional criteria such as structural, environmental, view, MEP amongst many can be quantified through numerical values and therefore easily measured and translated into sets of data. However, there are design criteria that are difficult to quantify using measurements and therefore parameterizing these criteria into sets of values to be used in design process are not straight forward. Even when they are successfully converted into values, the evaluation process based on these criteria relies partially on the designer own judgments. Among these criteria are communicative performances, social functions and aesthetical values, all of which are essential part of designing a building. Shell design process in building scale projects includes these evaluation criteria as a part of the design decision making process. Within the shell morphologies designed by ZHA, the topological variations consider way-finding and programmatic use. The computational processes using crowd simulation to integrate these architectural values are currently at an experimental stage. In ZHA's projects with shell topologies, one of the aims has been to create differentiated spaces that can house the environment suitable for their function with legible order through topological variation. Design intentions are often expressed with the articulated roof structure that is following the tensile shell logic and the load distribution lines to maintain the underlying engineering logic of the design legible. These ideas have been tested in several projects including Qingdao Culture Centre and presidential Head Quarter in Algiers.

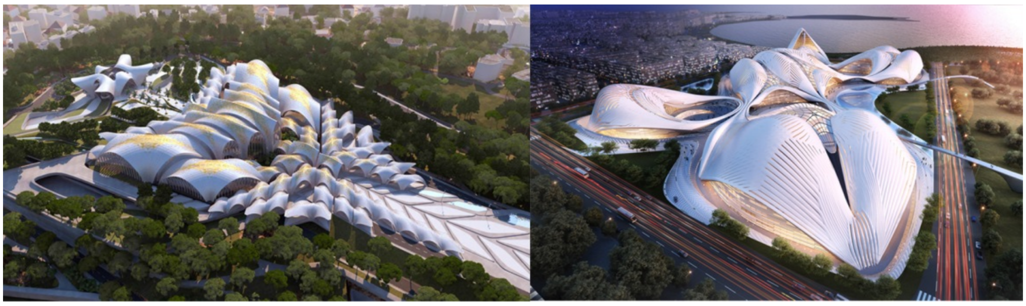

Figure 13 (Left). Presidential Head Quarter in Algiers, Algeria
Figure 14 (Right). Qingdao Culture Centre, Qingdao, China

Construction of large scale structural surface is limited by the available construction technology and budget in most cases in current building industry. Although conceptually thought of as an integral structural skin, often it is constructed as a layer of cladding and substructure where only together they provide enclosure and self-supporting structural integrity. Some of the reasons for these types of constructions are budget, the scalability of the material which can build doubly curved structural surface and sometimes local building regulation. The design of the self-supporting structural surfaces with complex form requires geometric solutions such as tessellation strategies to subdivide the global geometry into constructible pieces as well as the solution for fabrication methods. When realizing a building with doubly curved surfaces, it is a common occurrence to go through a process of geometric rationalization in the later stages. The panelization is often done considering the available material and construction skills, global geometry and budget. This process often leads to rationalization and systematic penalization of the global geometry and is studied with an iterative process using parametric tools. The budget of the construction typically determines the degree of adjustment that needs to be carried on the global geometry and a large degree of modification can compromise the embedded intelligence of the morphology. Therefore it is essential to integrate the tessellation strategy together with the material system of the cladding and the fabrication methods. The construction of the external cladding of Dongdaemun Design Plaza(DDP) in the following section highlights how the fabrication method together with the material intelligence aided the construction of the complex surface.

4.3.2 Dongdaemun Design Plaza (DDP), Seoul, Korea

The shell inspired massing of DDP is realized as the largest column-less construction in the world and is built using truss and space frame structural systems which follows the shape of the envelope. The massing as one entity locally deforms to react to functional needs of the building to provide passages, shading, landscape, entrances, plaza among others for both indoor and outdoor spaces while maintaining the seamless continuity in both the massing and spatial fluidity. From architectural point of view, the design of the external skin carries semiological intelligence. Conceptually in this case, the external skin is synonymous to the massing due to the fact that massing and envelope are one entity that describes the architecture without the distinction between the structure and form. Therefore the building envelope carries the intelligence of aforementioned architectural design intent with an added layer of transparency in materiality to reflect the programmatic needs of the localized areas.

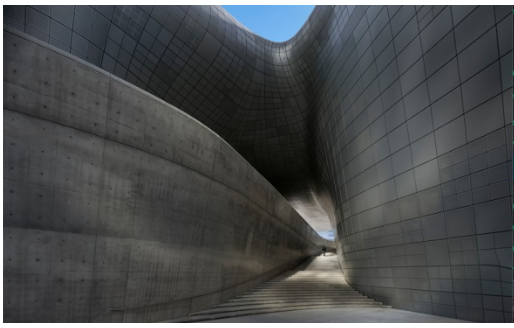


Figure 15 (Left) DDP external cladding view (Photos © Virgile Simon Bertrand)
Figure 16 (Right) DDP (Photos © Virgile Simon Bertrand)

The external cladding was constructed with programmable material which allowed for varying degree of surface curvature to be achieved at ease with relatively low construction cost. The fabrication of the external cladding of DDP allowed for mass-customization of unique panel types using parametric modelling and advanced metal forming fabrication methods. The cladding is made up of over 45,000 panels in various sizes and degrees of curvature. The fabrication process relied on the malleability of sheet metals which are pressed to obtain the desired curvature. Advance technology using 3d marking robots, multi-point form machine and multi-point stretching forming machines were used in the process. The parametric model of the cladding system provided the point coordinates and deviation of centroid to the cross centre of each panel to describe the deformation. These set of data extracted from the 3d model are used as input for machine operated process to first use the punch module calibration method to obtain the general curvature and panel forming process to refine the curvature of the panels (Figure 17). The tessellation methods of the external cladding optimized each panels to be fabricated within the constraint of the material properties of the metal sheets and degree of deformation resulting in the distribution of smaller panels for the areas with more extreme curvature. Using this design to fabrication process, it was feasible to realize the complex form while keeping the cost at bay.

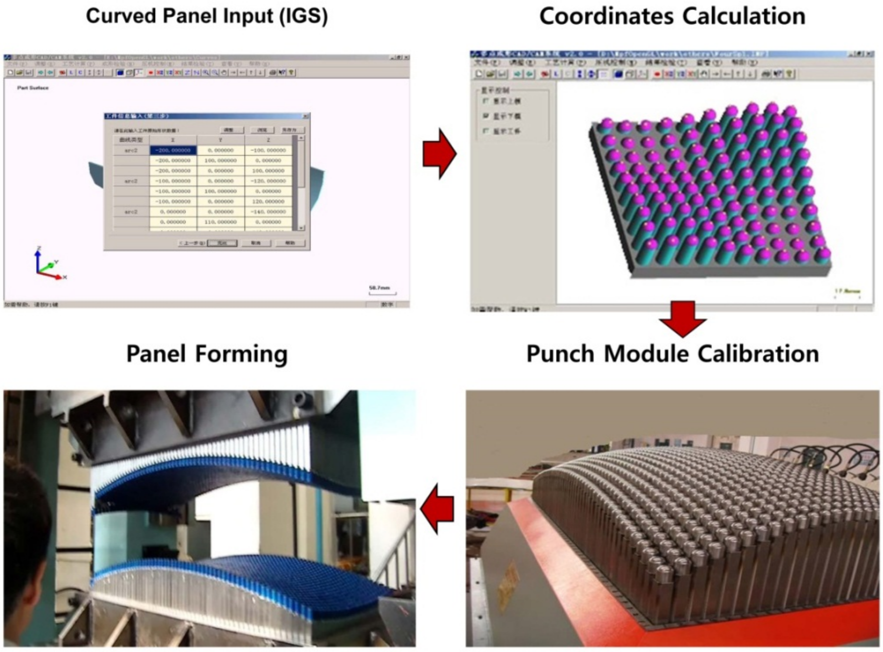

Figure 17. DDP Advanced 3D Methods- Multi-pin Stretched Forming

5. Conclusion

This paper illustrates potentials of self-supporting curved surfaces as multiperformative morphologies which can encompass structure, material, and architectural performances in its form. Through various projects, this paper aimed to point out the factors that can influence the manifested morphology of the shell structure throughout the design stages from the early form finding to construction.

The computational form finding techniques and the research driven design thinking are currently more prevalent in academia or among highly specific engineering related professionals. Currently, there is a limitation in real world practice to integrate seamless computational work flow derived from simulation and performance oriented form finding to construction process to integrate fabrication techniques and material intelligence. This is due to multiple factors that are as subjective as individual designer's design preference to reasons as broad as the division within the current construction industry. For this reasons, the projects included in this paper with research agenda to integrate form finding process and construction are carried out as prototypes. Whereas selected aspects of the large architectural scale projects are emphasized mainly to highlight the areas in which design innovation can be achieved through simulation driven process and fabrication intelligence.

As mentioned previously, the intelligence and information that can influence morphologies are spread over the domains of architecture, engineer and fabrication. The engineering and fabrication criteria are well established and are adopted within the practices through customized tools and computational procedure as exemplified in the works of CODE. It is the architectural criteria that the computational design methodologies can be further developed to use tools such as crowd simulation to better inform the morphology of a project. This process is currently in an experimental stage that needs further development.

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