Bending Active Grids as Secondary Structure

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Abstract

The implementation of grid shells is reduced to experimental pavilions, temporary structures, and research projects. All things considered, the geometric properties of grid shells must be put into good use in permanent applications to take full advantage of the said properties and the geometric shapes they produce. An interesting approach to these fascinating structures is a facade system which aims to improve the existing structural envelope systems in the market. Double skin facade is an integrated system capable of reducing heating demand, creating a pollution barrier, providing acoustic insulation and can promote natural cross ventilation, as well as reducing radiation, all of which is to improve the inhabitants' comfort and the building's energy efficiency and aesthetics. While we might be more familiar with their advantages, there are some disadvantages we must take into consideration in order to move forward and get the most out of a system. Bending active grids have many properties that might serve the objective of mitigating some of the disadvantages. It's more convenient to use a lightweight system that's manifested as a vertical grid shell that works as a double skin yet fluid envelope which can be deployed over existing structures to improve its aesthetics or as a premium design of a building. Thus, in this article, the details of the process, including Form-finding, structural, radiational analysis, study of the material, and the implemented grid shell system, which resulted in the success of this implementation to shed light on the most convenient advantages of this innovative approach, showing to what extent this method can push the design of any double- skin façade building envelope.

Keywords: double-skin façade, bending-active, louvres, optimization, grid-shell structures, light-weight structures, deployability.

1 Introduction

The rise of big cities has resulted in a need for skyscrapers, and the recent regulation regarding environmental issues required a solution that is energy efficient. The solution for these issues arose in the early 80’s in form of double-skin façade, often known as the DSF, composed of two transparent skins: an external façade, an intermediate area, and an internal façade. The glazed outer layer provides weather protection as well as enhanced acoustics. In the intermediate area, an adjustable sunshade device could also be installed to shield the internal rooms. [1] While it may be the best option in some cases, it’s high-cost structure that restricts architectural originality and flexibility. An inadequate combination of glass in a DSF can reduce the amount of natural light that enters a building while also raising the temperature in the intermediate Area causing condensation on the external skin. DFS is a structurally heavy construction that causes the building to carry great loads, which may be quite damaging to the foundation if installed to a pre-existing building.

All things considered, a flat orthogonal façade is heavier and significantly more expensive than per se, curved structures. A parametric skin, that is basically a vertical grid shell has the same advantages of a horizontal one and some of the most important ones are mentioned by Geometrica: “A grid shell's organic shape and column-free space provide unlimited design freedom to architects and structural engineers. These innovative space-frame structures derive their strength from having double curvature in their overall shape.” [2] Nonetheless, these constructions are limited by the selection of material and costs. Furthermore, due of the nonlinear geometries and organic forms, the study of bending active grid shells is complex. Other factors must also be taken into consideration, including the estimation of the required shape a flat grid will take when it’s assembled, and then the calculation the deformations and stresses that occur due to the grid shell’s own weight and the applied loads. In addition to the aforementioned considerations, it’s important to consider the stresses that occur during assembly and installation. In this case, the building’s exposure to radiation should be studied, showcasing different materials and situations in order to compare them utilizing radiation analysis, with the cost effectiveness of this invention being the main focus. [3] All while keeping in mind the difficulties that may arise while assembling and installing a vertical grid shell.

2 Case-studies

2.1 Double Skin Façade:

Asakusa Culture Tourist Information Centre

Figure 1: Asakusa Culture Tourist Information Centre [4]

Architect: Kengo Kuma & Associates

Completion Year: 2013

Location: Taito-ku, Japan

Material: Glass and Wood

Description of the case study:

The center vertically expands Asakusa’s dynamic neighborhood and stacks roofs that surround various activities beneath, creating a “new sector” that did not exist in traditional design. It's mostly composed of glass and wood, and the interiors are light and airy. Excess sunlight is filtered by vertical wooden louvers that wrap the building's eight levels, providing the sufficient need of natural light.

The double skin façade used in this building not only helped in dividing each of the floors, but it also assisted in defining the function of each level but the level of exposure through the skin and height of the roof. [4]

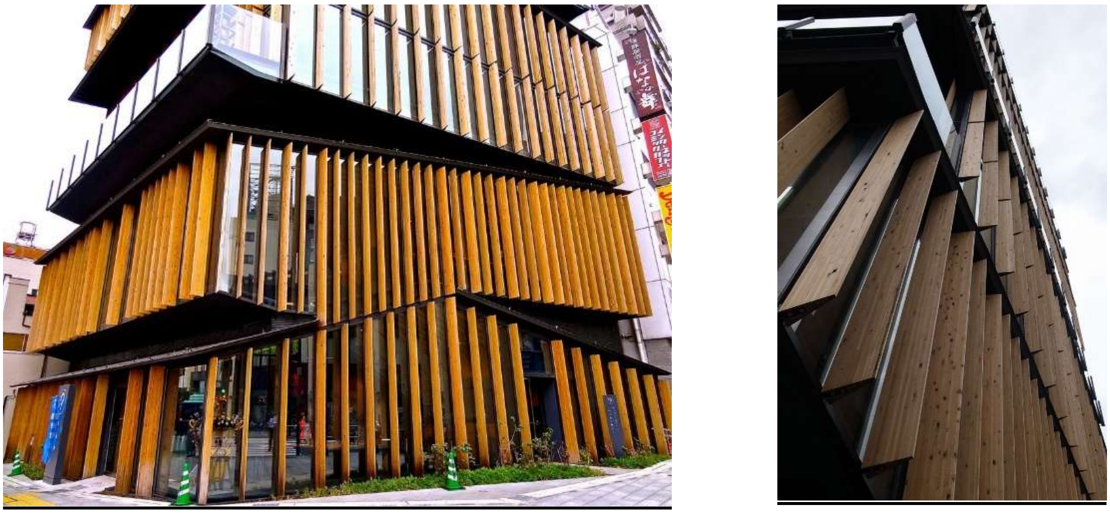


Figure 2: Asakusa Culture Tourist Information Centre [4]

Bibliothèque National De France

Figure 3: National Library of France [5]

Architect: Dominique Perrault

Completion Year: 1996

Location: Paris, France

Material: Glass and Wood

Description of the case study:

The double façade is layered and visually intriguing. The wooden screens that protect the books age and develop a patina without causing any damage to their aesthetic value. Glass, steel, and wood are integrated here to give the reading rooms a sense of cohesiveness and originality.

Based on the abundant ways this façade can be treated, a variety of solutions were devised depending on the type of space to be treated. These range from the Lobby / Vestibule to the reading rooms, through stacks and various storage places of all kinds as well as the wooden screens that act as a key element. [5]

Figure 4: National Library of France [5]

European Council and Council of the EU

Figure 5: European Council and Council of the European Union [6]

Architect: SAMYN and PARTNERS

Completion Year: 2016

Location: Brussels, Belgium

Material: Glass and Wood

Description of the case study:

As part of a sustainable development strategy, it was decided to restore and revive certain ancient, but still functional window frames. The double-glazed facade is obtained through an outer skin patchwork of recycled antique oak wood windows acquired on demolition sites with crystal clear single glazing and an inner skin patchwork of the same glazing material make up the glazed double façade.

The main feature that is quite unique in this double façade system is how it reflects on usage of the meeting rooms and how it enhanced the experience on the interior of the building not only as a façade or exterior treatment, in other words it shaped the way people activate the space. [6]

Figure 6: European Council and Council of the European Union [6]

Market Hall in Ghent

Figure 7: Market Hall in Ghent [8]

Architect: Marie-José Van Hee Robbrecht & Daem

Completion Year: 2012

Location: Ghent, Belgium

Material: Glass and Wood

Description of the case study:

The structure is situated in the heart of Ghent, near to old stone structures. Its purpose is to encourage locals to meet in the market square for social gatherings and public events. Concrete columns, a steel-framed roof, and wood cladding are among the building materials. A glass wrapper also preserves the wood and gives it a lovely sheen, with sky reflections.

Despite the fact that the structure stands out on the 24,000m^2 plot, it blends in pleasantly. And the double skin used breaks the contrast between the surrounding building in an orderly manner to provide better aesthetics and thermal functions for the structure itself. [8]

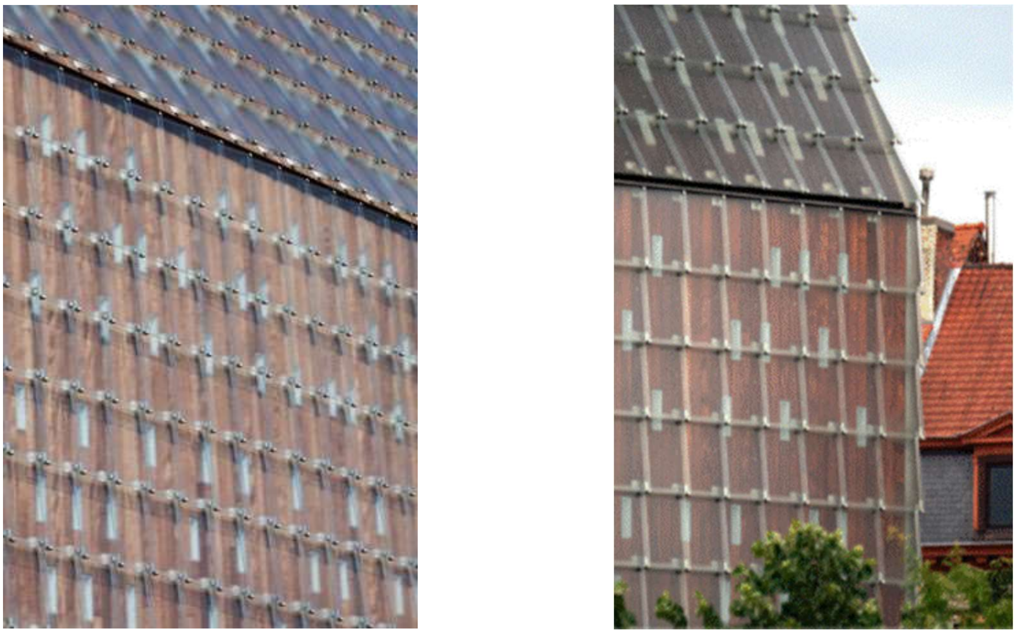


Figure 8; Market Hall in Ghent [8]

2.2 Membrane façades

“In architecture and construction, membranes refer to **façade or roof skins**, which are made from mechanically or pneumatically pre-stressed textile fabrics or foils.” [9]

Yujaipo Railway Station

Figure 9: Yujaipo Railway Station [7]

Architect: Arup Architecture Firm

Completion Year: 2015

Location: Tianjin, China

Material: Tensile Fabric

Description of the case study:

This Railway station is iconic and most well-known for its famous roof, which is 148 meters long, 83 meters broad, and 25 meters tall, is one of the most technically complex aspects of the project. The ability to realize the groundbreaking architectural concept thanks to long span roof design knowledge. Its important to take into account that the integration of several design disciplines, the structural behavior and on site logistics make the implementation of this project a very convoluted task.

The dome of Yujaipo Station was designed using a combination of steel structure and tensile fabric architecture, creating a membrane façade system considering the lighting of the underground station and the load-bearing of the dome. ETFE membrane material, which has strong tear resistance, high tensile strength, medium hardness, excellent impact resistance, long telescopic life, and strong light transmission, is used to construct the shade shelter. [7]

Figure 10: Yujaipo Railway Station [7]

US Embassy in London

Figure 11: US Embassy in London [10]

Architect: Birdair Inc. and Taiyo

Europe GmbH.

Completion Year: 2018

Location: London, UK

Material: ETFE Membrane

Description of the case study:

With a covering area of more than 8000 m^2, the sail-like ETFE elements (total of 399 units) envelop the building in all directions except north, mounted on a 180 Ton aluminum and carbon steel structure frame. Unlike other façade system installations, this one was difficult to complete since it required rope access. This was overcome thanks to the installation crew's skill and coordination. The ETFE shades help to reduce sun radiation and glare while allowing natural light to be diffused evenly into the building. The transparent façade appears to change color depending on the weather and the position of the sun. [10]

Figure 12: US Embassy in London [10]

Canary Wharf Railway Station

Figure 13: Canary Wharf Railway station [11]

Architect: SAMYN and PARTNERS

Completion Year: 2014

Location: London, UK

Material: Recycled Aluminium & ETFE

Description of the case study:

The Cross-rail Station in London is located near the waters of Canary Wharf's North Dock, just meters from the Foster & Partners-designed underground station. A ticket hall and platforms will be located below sea level, with four above-ground stories housing stores, restaurants, as well as a cinema

The latticed structure's triangular modules are paneled with either recycled aluminum panels or translucent ETFE plastic cushions that allow natural light to pass through. Some modules in the middle of the structure have been left open, allowing rainfall and light to fall into a lush central garden. This massive London project, which combines a train station, a commercial zone, and a green park. [11]

Figure 14: Canary Wharf Railway Station [11]

Climate facade by Koch membranen

Figure 15: Climate facade by Koch membranen [12]

Architect: Koch Membranen

Completion Year: 2016

Location: Germany

Material: Pneumatic Foil Cushions

Description of the case study:

Low weight, remarkable durability, and, in certain circumstances, outstanding self-cleaning qualities are all advantages of textile facade structures. The organic shaping of the structures, as well as the different degrees of translucence - translucent or lighted – are at the heart of textile architecture's attraction.

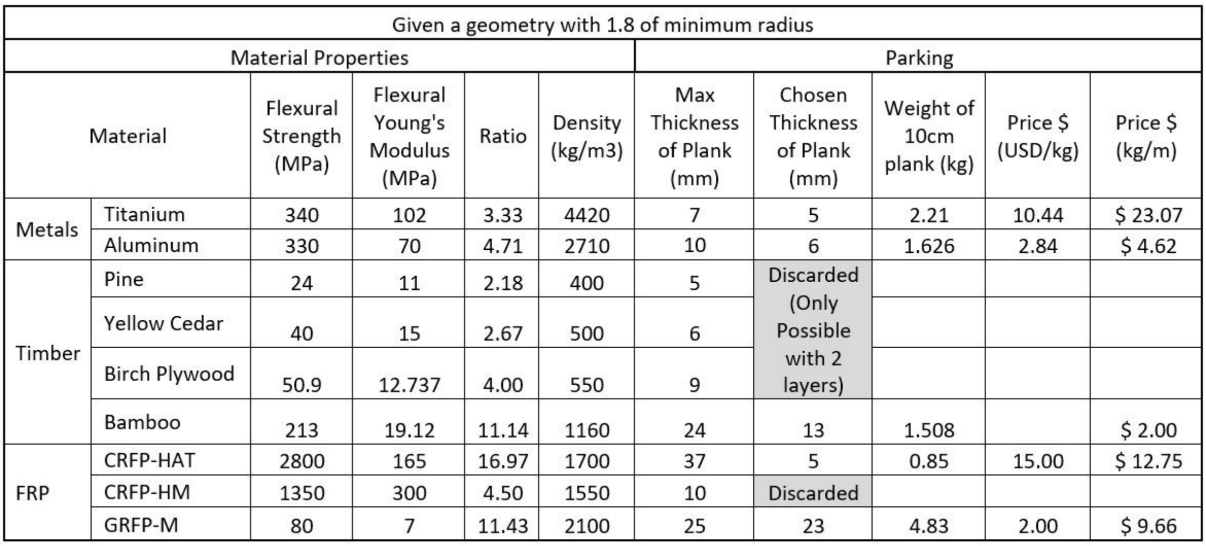
The chosen materials and their surfaces give the finished architecture its particular appearance and feel, whether it's wide-arching cloth or pneumatic foil cushions. The material is always chosen to precisely match each application. The design ideas, ambient and climatic circumstances, and considerations like as light permeability, durability, and cost all influence the material selection. [12]

Figure 16: Climate facade by Koch membranen [12]

2.3 Active-bent Structures

Active bending is a form-finding process that occurs when an elastic rod or plate structure is deformed. It's a method for creating curved geometry out of flat, straight elements or surfaces. [13] A study about materials used in active bending structures states: "Active bending structures need materials with specific mechanical properties such as large admissible strain and sufficiently high stiffness to prevent buckling." The most affordable materials used in active-bending grids are glass fiber reinforced polymers (GFRP) and natural fiber reinforced polymers (NFRP). [14].

Table 1: Properties of common building materials in active-bent structures [15] [16]



Given a geometry with 1.8 of minimum radius										
Material Properties						Parking				
Material		Flexural Strength (MPa)	Flexural Young's Modulus (MPa)	Ratio	Density (kg/m3)	Max Thickness of Plank (mm)	Chosen Thickness of Plank (mm)	Weight of 10cm plank (kg)	Price $ (USD/kg)	Price $ (kg/m)
Metals	Titanium	340	102	3.33	4420	7	5	2.21	10.44	$ 23.07
	Aluminum	330	70	4.71	2710	10	6	1.626	2.84	$ 4.62
Timber	Pine	24	11	2.18	400	5	Discarded (Only Possible with 2 layers)			
	Yellow Cedar	40	15	2.67	500	6				
	Birch Plywood	50.9	12.737	4.00	550	9				
	Bamboo	213	19.12	11.14	1160	24	13	1.508		$ 2.00
FRP	CRFP-HAT	2800	165	16.97	1700	37	5	0.85	15.00	$ 12.75
	CRFP-HM	1350	300	4.50	1550	10	Discarded			
	GRFP-M	80	7	11.43	2100	25	23	4.83	2.00	$ 9.66

Some of the most used material in the construction of grid shells are the ones mentioned in (table.1), and that's due to specific their properties including flexural strength, elasticity, etc..

2.3.1 Deployability and shaping of a 2-way grid shell (scissor) system

The benefits active-bending in the shaping process of a 2-way grid shell may be further highlighted with a free-form made out of straight laths joined in nodes. These straight elastic continuous laths might converge to the nodes from different angles to be screwed and bolted in conventional and simple connections. When said laths are placed in a geodesic grid, they form a rib that bends solely around the weak axis and has no geodesic curvature. [17]

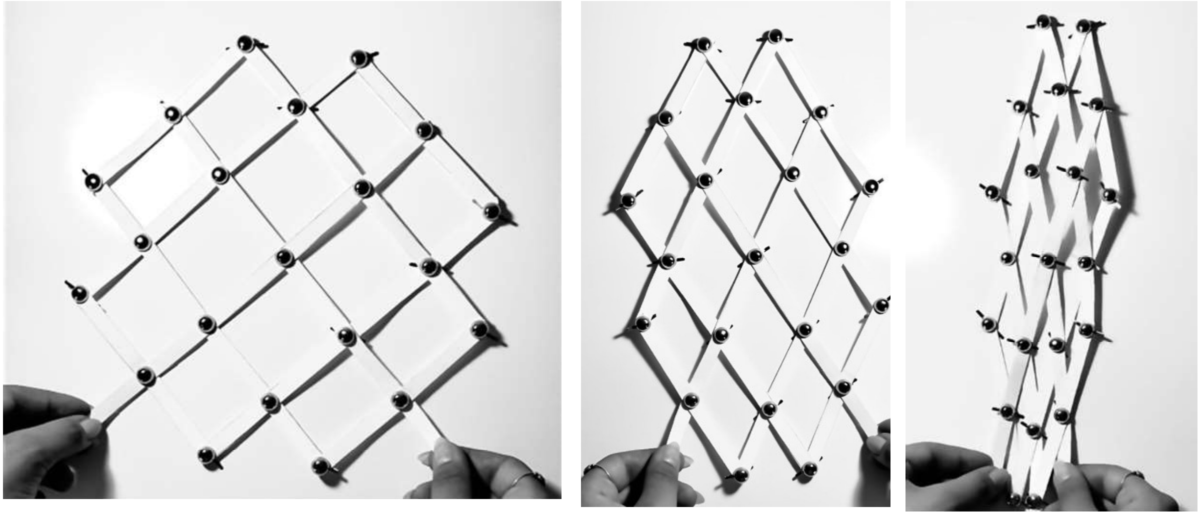


Figure 17:Scissors system (Click here to watch the video)

A 2-way scissor mechanism allows for this system to be easily deployed as shown in *(fig.17)*. This allows for prior assembly of the grid shell, facilitates transportation, and assures time efficiency in the process of applying this grid shell and shaping it into its ultimate form. The support points make the grid adaptable and fluid so it bends in the way it's designed to be, shaping it into the desirable form *(fig.18)*.

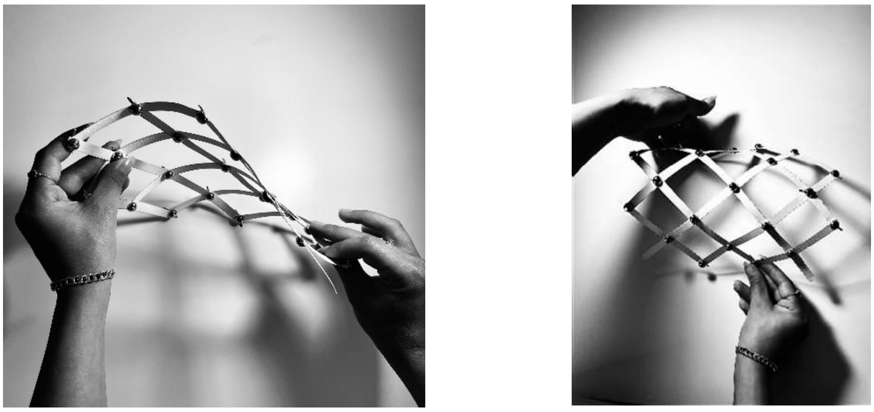


Figure 18: Shaping and curvature.

3 Application Process:

To accomplish the objective of this parametric DSF, the form-finding process was aimed towards a double-curved surface. (fig.19) The aforementioned surface may be generated using any desired technique and process. However, the approach in this case was to start out with a revolutionary curve controlled by a sine function. It's important to emphasize the necessity of evaluating the curvature of the stated surface to ensure that it doesn't exceed the minimum radius of curvature that elastic material can accomplish within their limitations. There is a variety of materials possess these characteristics, however their application and elastic state are constrained. (Table.1)

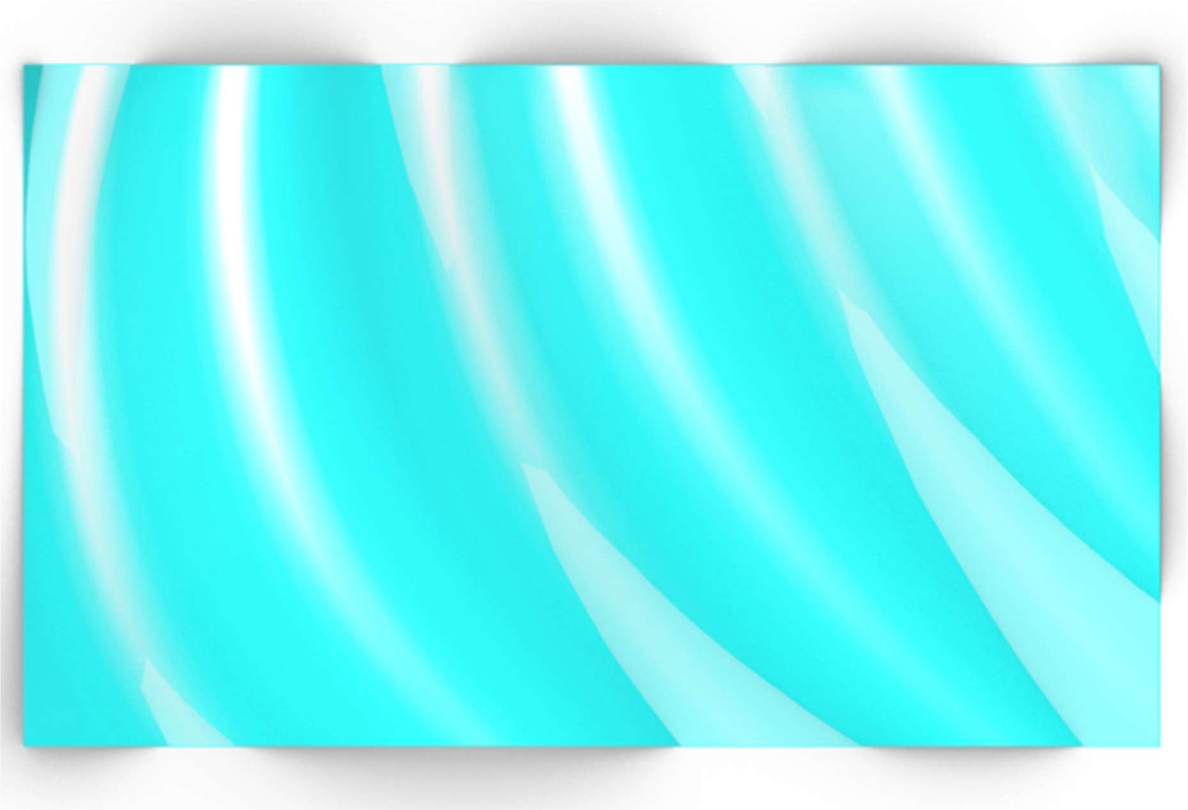


Figure 19: The target surface

The following step consists of finding the mesh that will make out the grid, which is achieved by dividing the front view while working in 2D, considering that the floor slabs would hold the support points. This is done by a plane mesh. Each of the faces of the mesh would make out 1 unit. By connecting the edges of these faces results in the desired diagonal mesh for these units. (fig.20)

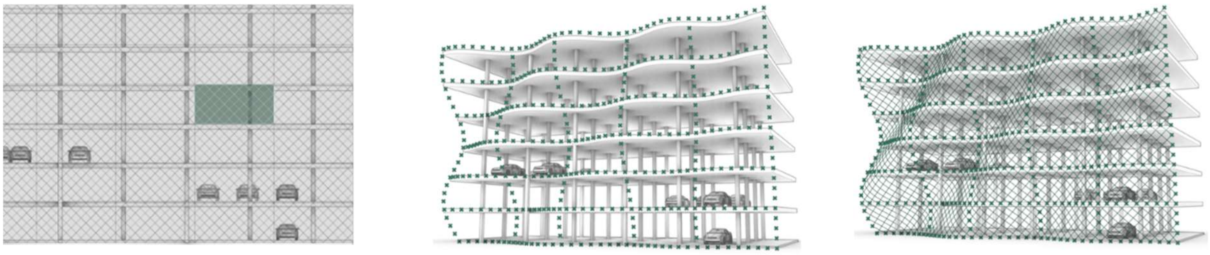


Figure 20: Finding the final grid

After getting the grid which would be the base of a rectangular mesh that's composed of smaller diagonal meshes, from which we can extract sorted end points of the diagonal lines in order to project them on the target surface. With the points sorted in that manner, drawing geodesic curves from these end points and the diagonal curves is a simple and controlled process. Ultimately making up a geodesic grid over the target surface which are also coincident to the nodes of support installed on the floor slabs. These units of grids eventually add up to describe the whole of the target surface as seen in (fig.20). The curves can then be offset to create the volumes of the bent planks. The fabrication files are created through the curve's lengths and intersection points which would be grid connection points.

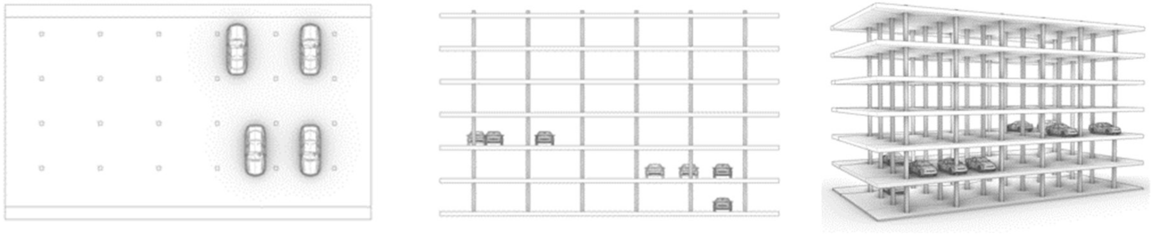


Figure 21: Suggested building before optimization

The floor slabs of the suggested building are trimmed to follow the shape of the target surface(fig.19), in order to create the needed support for the grid shell's implementation. (fig.22)

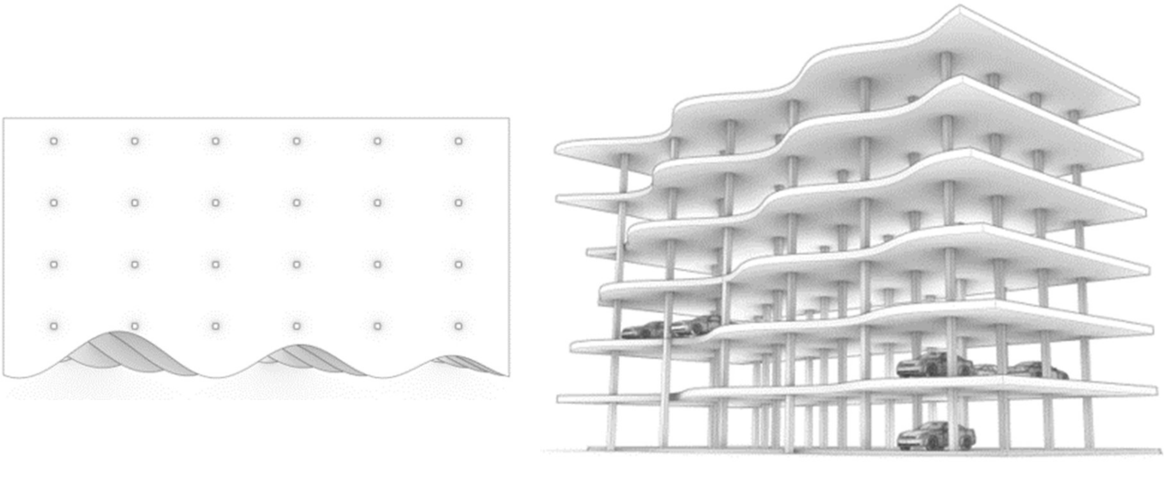


Figure 22: Trimmed slabs from top view and shown in 3D

3.1 Structural Analysis

For the purpose of comparing the structural behavior of different materials with different plank thicknesses, a non-linear structural analysis was made using the isogeometric analysis plug-in in Grasshopper of Rhino called Kiwi.
Using the specified grid and target surface, the analysis was performed on one unit of the façade in terms of self-weight and wind conditions.
The Spanish code "seguridad estructural y acciones en la edificacion" isused to compute wind loads, in which a constant load is given to the typical direction of the façade using the simplified equation:

$$qe = qb + ce + cp$$

These loads are applied to five different materials with varied plank thicknesses. Each one causes the structure to bend to the point where maximal distortion can be seen. (graph /fig.24)
Each material choice in the graph has a pattern that can be observed, a cutting line "A" is selected to indicate the maximum deformation, which is set to 0.3 mm, in order to obtain the weight and cost of each material option in addition to line "B" that is set at 1 (table 2). This analysis is just for the purpose of assessing alternative material possibilities; it is not a proper structural analysis for the purpose of designing the structure. It can be concluded that GFRP is the most cost-effective material for these structures, and that its low maximum radius allows it to be used in a broad range of shapes.

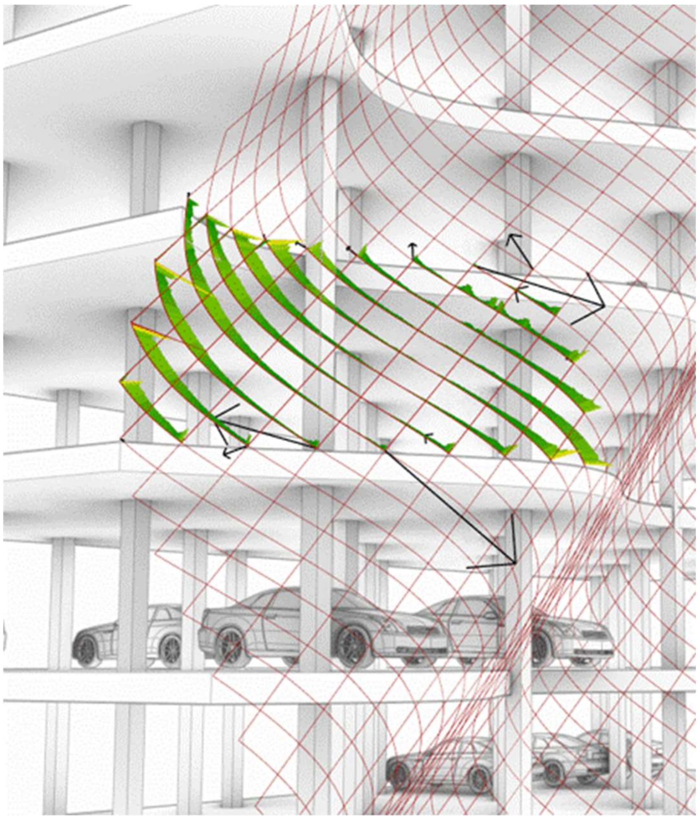


Figure 23: Grid shell unit Analysis

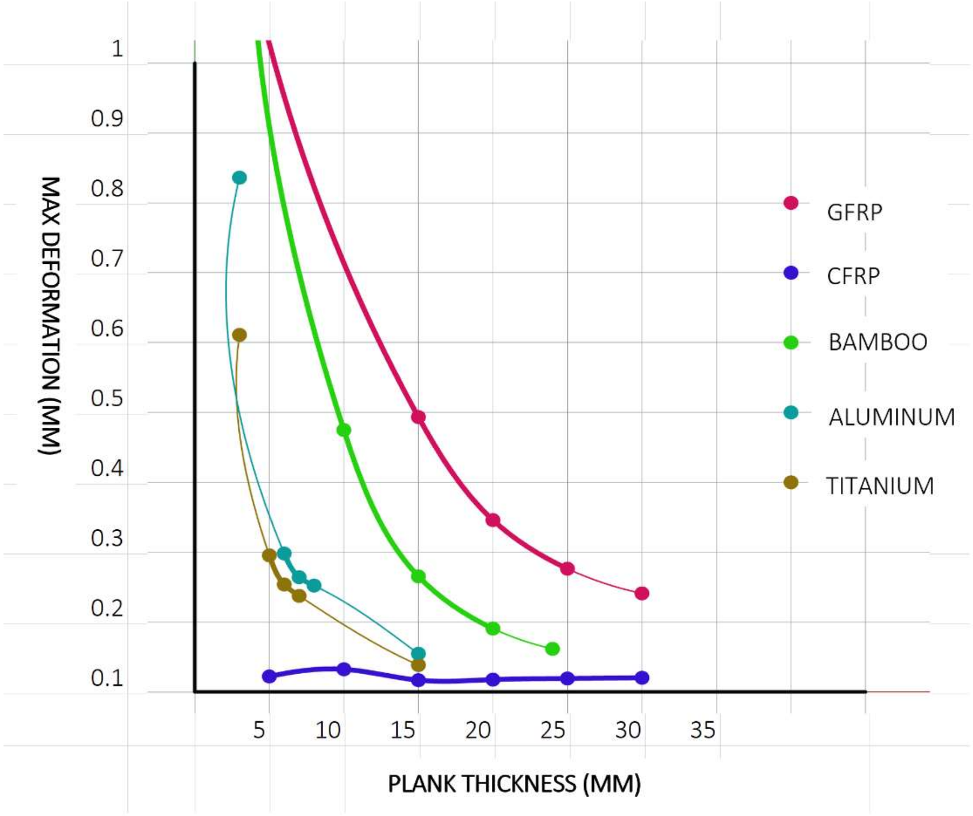


Figure 24: Graph demonstrating the plank thicknesses vs. maximum deformation for different materials

	Max deformation at 0.30 mm		Max deformation at 1.00 mm	
	Plank Thickness	**PRICE $ (USD/m)**	Plank Thickness	**PRICE $ (USD/m)**
Titanium	5 mm	$ 23.07		
Aluminum	6 mm	$ 4.62		
Bamboo	10 -15 mm	$ 2.00	10 - 15 mm	$ 2.00
CRFP-HAT	5 mm	$ 12.75		
GRFP-M	23 mm	$ 9.66	6 mm	$ 2.52

Table 2: Material's thicknesses and prices in reference to their maximum deformation point.

3.2 Radiation Analysis:

This Analysis was done using Ladybug, an environmental analysis plugin for Grasshopper for Rhino. Ladybug combines geometry in Rhino and the parametric interface of Grasshopper with open-source weather data from EnergyPlus (.epw files) to create site specific climate analysis graphics and diagrams. (Baker Lightning Lab, 2021) The objective of this analysis is to showcase distinct systems of envelopes of an office building including the fore mentioned innovation in multiple scenarios, assessing the design options through solar radiation studies in (kw/h).

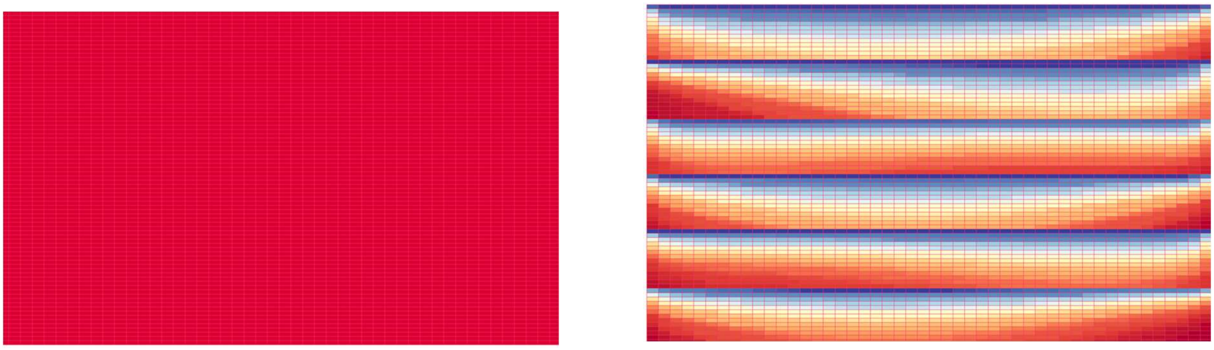


Figure a: Glass Façade

Figure b: Glass facade + Corridors

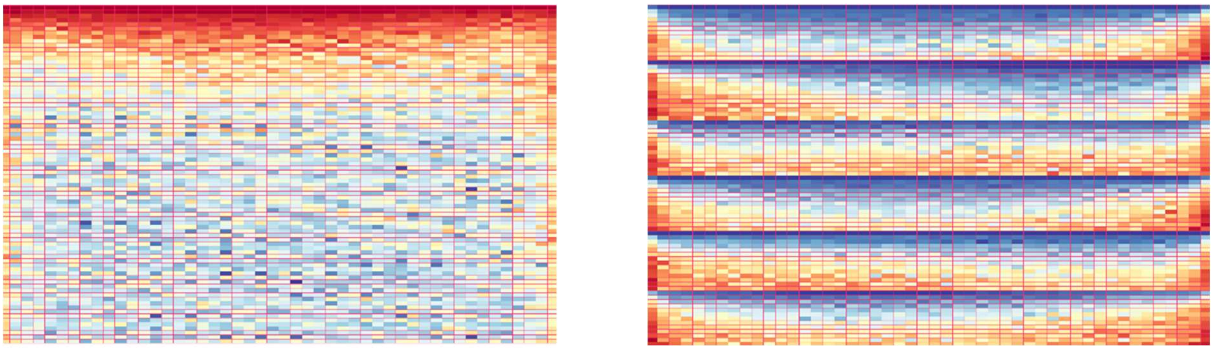


Figure c; Glass façade + Grid shell

Figure d: Glass Facade + Corridors + Grid shell

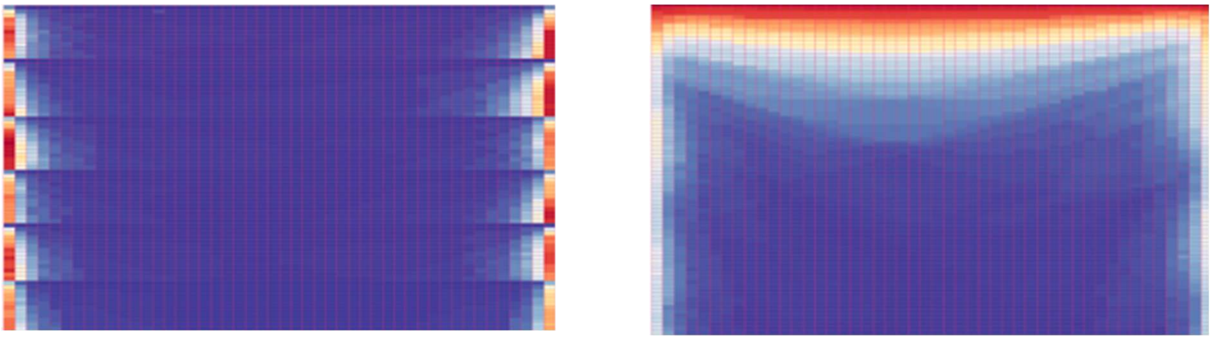


Figure e: Glass Facade + Corridors + Grid shell +Membrane

Figure f: Glass Facade + Grid shell +Membrane

Figure 25: Radiation Analysis of an Office Building using different façade systems

This study of various scenarios has been applied by inserting obstructions along the process of analysis, As shown in (fig.25): figure (a) represents a regular office building with a glass façade showcasing how the whole entity of it is exposed to radiation. (b) with added corridors that lessened the radiation right at the bottom of them. (c) showcases a scenario where the grid shell was implemented over the glass exposing the building to radiation mostly at the highest contour of its façade, as it becomes mildly to less exposed where it's covered by the said grid shell. (d) includes all of the formerly mentioned obstacles (Glass, corridors, grid shell), which has shown a decrease in radiation exposure. Last but not least, in (e), where a membrane has been added, there's little to no exposure to radiation that is reduced just to the side contours of the envelope. In the last specimen of this study, the building is obscured by a membrane, grid shell and a glass façade removing the corridors from the equation leading to the results shown in the last graphic visual (f), in which the whole façade is protected from the radiation expect for the top contour line where it's exposed to the sun.

All of these barriers lessen radiation, and the outcomes are presented in an estimated cost/sq. for each of these cases. (Refer to fig.20).

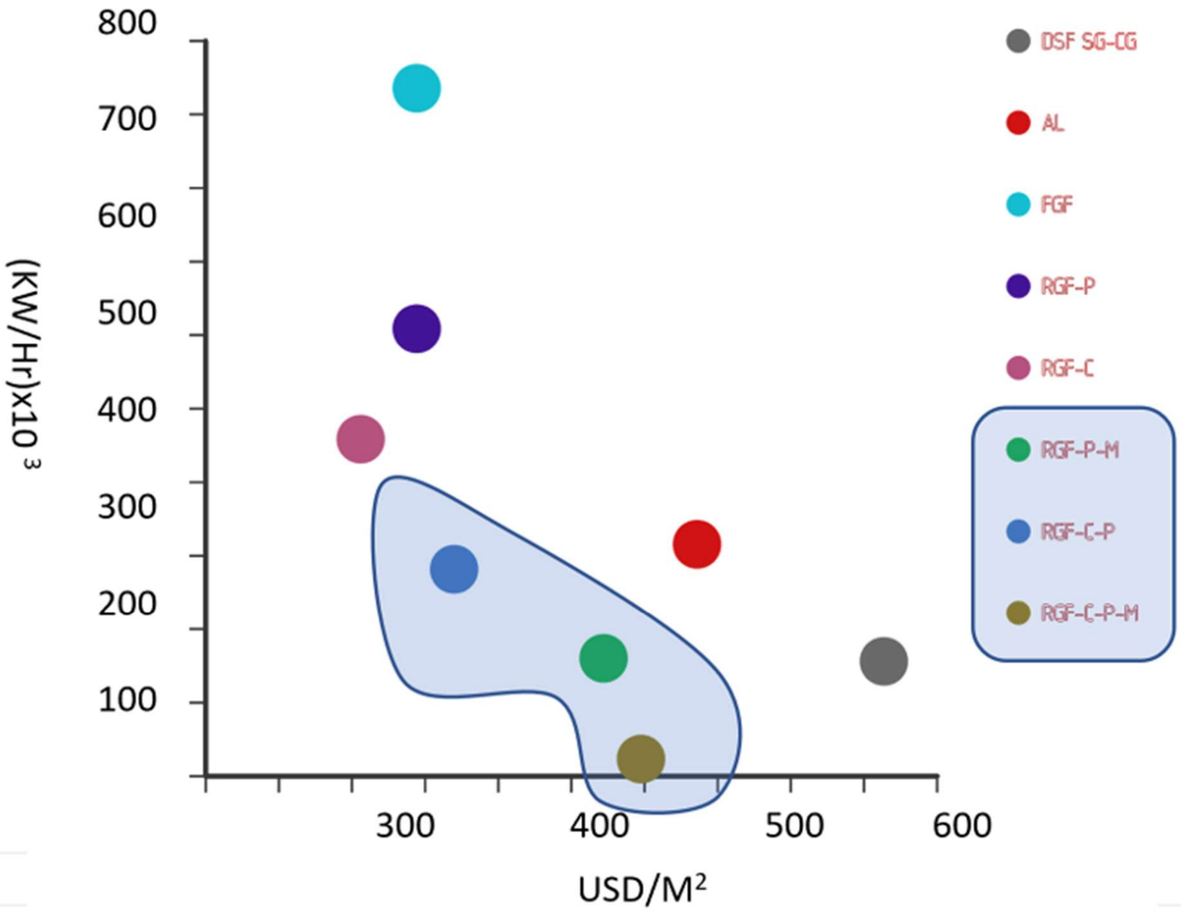


Figure 26: The various façade systems' exposure to radiation and their estimated cost in $\$/m^2$

Legend of (fig.26):

DSF-SG-CG: DSF- simple glass -clear glass
AL: Aluminum louvres
FGS: Fancy glass façade
RGF-P: Regular glass facade – planks
RGF-C: Regular glass facade -Corridors
RGF-P-M: Regular glass facade – planks -Membrane
RGF-P-C: Regular glass facade – planks – Corridors
RGF-P-C: Regular glass facade – Corridors- Planks – Membrane

These combinations of building envelopes not only have different exposures to radiation but also a varying cost (fig.26). According to our study, the highest radiation value has been the outcome of a glass façade, one of the lowest values is the double skin façade made using the conventional method, while the façade exposed to least exposure is the DSF with the parametric outer skin covered in a membrane. In the blue zone, are the envelopes in which case the innovative parametric skin was implemented: All three cases are of least exposed to radiation and of the lowest costs, giving a solid proof that this innovation in indeed updating the system and improving its properties.

Figure 27: Visualization of the parametric DSF covered with a membrane.

3.3 Implementation:

In theory and considering the deployability of this system as shown in (fig.17) the implementation method would be to assemble these grid shell units in a workshop and transport them as small units to the designated site, while it might also be a possibility to implement it on site. The next step would be to lift it up with a crane, fixating it to the support point over the slabs and suggested extra columns (fig.28) with a free rotation joint that gives it flexibility on all 3 axes, and acts as a support system that facilitates the installation.

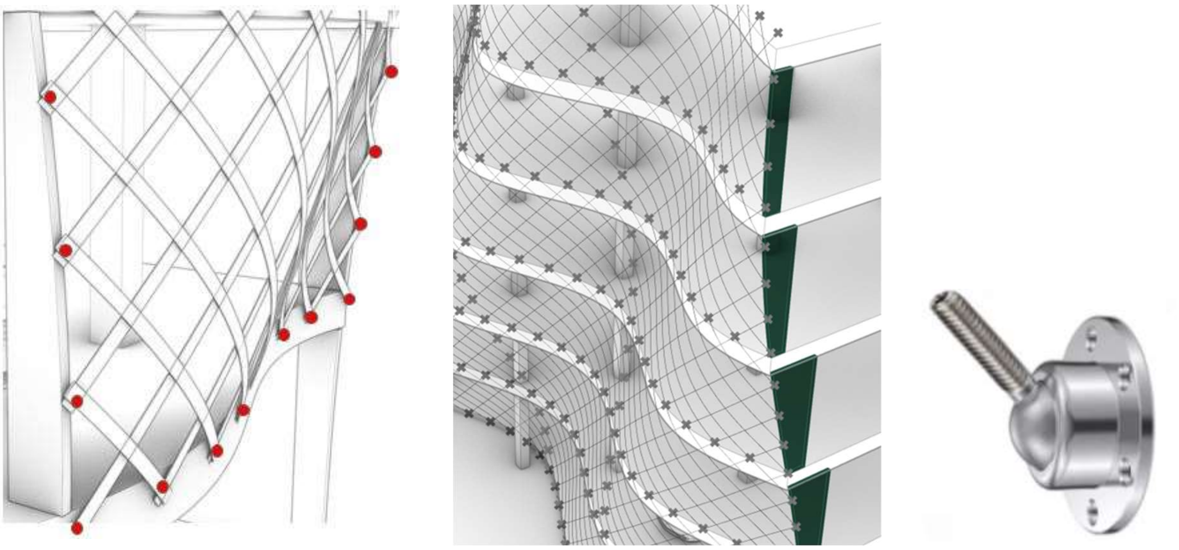


Figure 28: Fixation points on slabs and added columns and suggested added joint

3.4 Cylindrical Grid shell Design Process

Given a typical multi-story apartment building with a cylindrical shape, a freeform open enveloping surface is proposed. Then the slabs are projected to this surface to act as a supporting system for the grid.

The design of this system followed the same protocol explained with the previous system just by starting instead of a plane mesh, with a cylinder mesh.

Figure 29: Design Process Visualization

A cylindrical mesh is set as a base for the projection to the final surface. Support points should be arranged into patches to draw geodesic lines of the target surface from point to point in both directions.

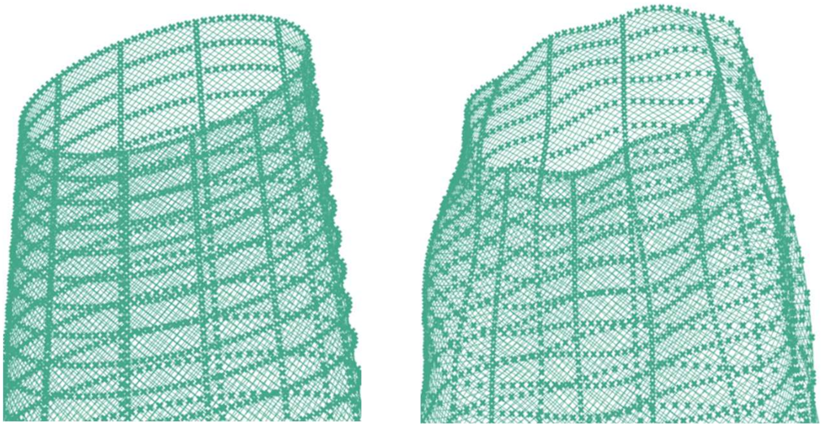


Figure 30: Projection point

Patches can be fabricated and cut by a CNC machine. Assembled, folded, and attached to the building with the proposed free rotation joints.

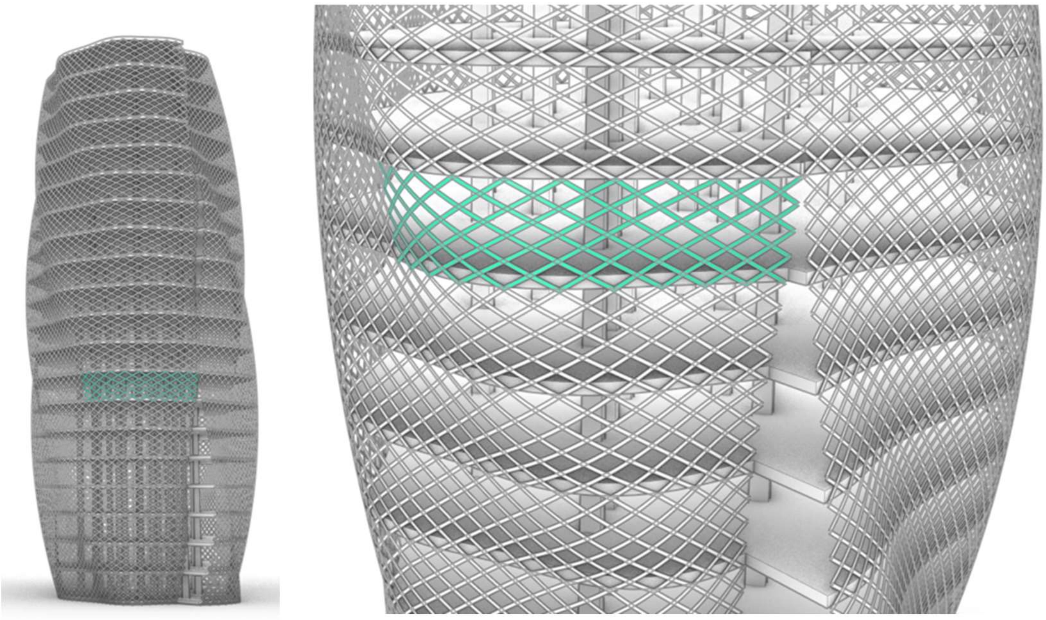


Figure 31: Cylindrical grid units

4 Conclusion:

To conclude, this parametric double skin façade has shown to improve the discussed points in the prior known DSF system through being a lightweight structure gaining its strength from its double curvature, being easily deployed with a range of various materials and less exposure to radiation while still being economically viable. This makes it the best option within the range of studied metrics. Nonetheless, it's a work in progress and further work is needed. Future work would include studies with various surfaces under various climate conditions and having options other than solely a front façade. Further research could be done on parametrizing the facade geometry to optimize the radiation performance or structural performance.

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