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A Generative Approach towards the Design of a Spherical Structural Envelope

Abstract: This article aims to describe the geometrical challenges that the structural design team encountered while approaching the structural modelling of the superstructure of the Apple Store at Marina Bay Sands in Singapore. Finite element analysis modelling followed a generative and parametric approach throughout the schematic, detailed and construction design stages. This enabled the structural design team to manage the geometrical complexity of the superstructure while fulfilling the architectural ambition. This study also focuses on how the structural design team made use of intermediary software (API) to streamline the modelling and analysis process. Several models were generated with the intention of studying the global structural behaviour and evaluating deflections, movements, buckling modes and the level of stress in the structural elements. In parallel, local detailed models were generated to evaluate stress concentration in the conical and spherical glass panels. Finally, this essay also retraces all the finite element models created to evaluate the alternative structural configurations that were explored during the design phase and helped define the path that led to the ultimate structural scheme.

Keywords: structural glass, finite element modelling, parametric design, spherical structural typologies

1 Introduction

This study focuses on the modelling challenges encountered by the structural glass engineers during the design phase of the Apple Store in Marina Bay Sands in Singapore. The iterative analysis process that led to develop the 30-metre diameter dome superstructure, which sits on a concrete podium surrounded by water, proved to be demanding, especially in terms of time and resources. This paper aims to explore how the analysis process was streamlined to maximise efficiency and cope with a challenging schedule throughout a generative approach.

The reader will find a review of selected spherical glass structures as well as advances on structural glass geometry typologies. The paper then describes the challenges of applying glass as main lateral force resisting structural system and the interactive methodology applied which culminated in an integrated analysis and parametric design workflow that empowered the spherical structural glass system design. With the methodology in place the author explores advantages or otherwise of the diverse geometrical morphologies tested, finally describing the structural glass approach taken for manufacturing and construction. The paper provides the results achieved and a

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Fig. 1: Apple Store retail unit in Marina Bay Sands, Singapore. (Photo by Finbar Fallon)

reflection upon the workflow that enabled the daring design and technology advances which together enabled achieving even more challenging frontiers on structural glass geometries.

2 Relevant precedents

2.1 Spherical glass structures

The Biosphere Environment Museum in Montreal, also known as Montreal Biosphere, designed by Buckminster Fuller and built as part of Expo 67 [1], established a fundamental precedent in dome structures. Although there are some precedents in geodesic domes, such as the Zeiss Planetarium in Jena [2], it remains an important example to be inspired by. It was originally covered by acrylic cells. The cladding system was lost during the 1976 fire. The building has a diameter of 76 m and height of 62 m. The structural system is based on a geodesic polyhedron tessellation.

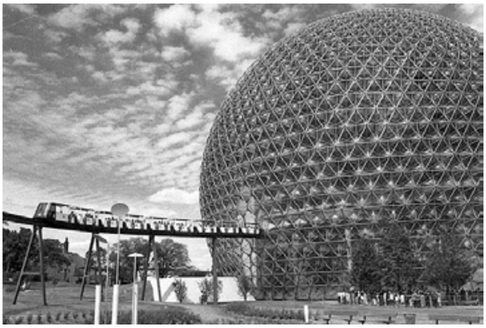

Fig. 2: Montreal Biosphere structure in 1968. (Archives de la Ville de Montréal, VM94-EX136-779)

Fig. 3: Biosfera Porto Antico, Genoa, Liguria. (Stock photo 1157076005)

Renzo Piano Building Workshop's Biosfera [3] established an important precedent in terms of glass spheres surrounded by water. The glass sphere has a diameter of 20 m and a height of 15 m and was completed in 2001 [4]. The structure is characterised by steel tubes organized in parallels and meridians, following the principal cuvature spherical lines, while bracing is ensured by steel diagonal rods. The glass is spherical and fixed to the steel superstructure by mechanical fixings.

The Montreal Biosphere, the first selected precedent, although represents a historic advance in spherical structures given its shear scale and geodesic geometry tessellation that has driven the structural members distribution, prior to the fire, had acrylic panels that were significantly smaller in scale, planar and used as cladding, i. e. with no structural performance. The second selected precedent, Biosfera, represents a similar location context in relation to the presented project. The glass panels, albeit spherical and following the spherical principal stress lines, have no structural load bearing and are supported by a large structure in relation to the case studied in this paper.

2.2 Advances in structural glass geometry

Recently, glass manufacturing processes and bending techniques rapidly evolved leading to the introduction of extra-large curved panels. The improvements across the industry, together with the increased desire for transparency, led to use of glass as structural element. Structural glass engineering had to follow at pace.

Apple Zorlu created a decisive precedent in terms of structural glass design [5]. The four glass walls are 10-metre wide and 3-metre tall. The walls are formed of 3 plies of laminated glass with ionoplast interlayers, while the roof is made of a single carbon fibre reinforced plastic panel. The glass walls work structurally to ensure vertical and horizontal stability of the whole lantern.

Another important reference in terms of structural glass design is given by the Steve Jobs Theatre in Cupertino [6], where the glass works structurally and is responsible for

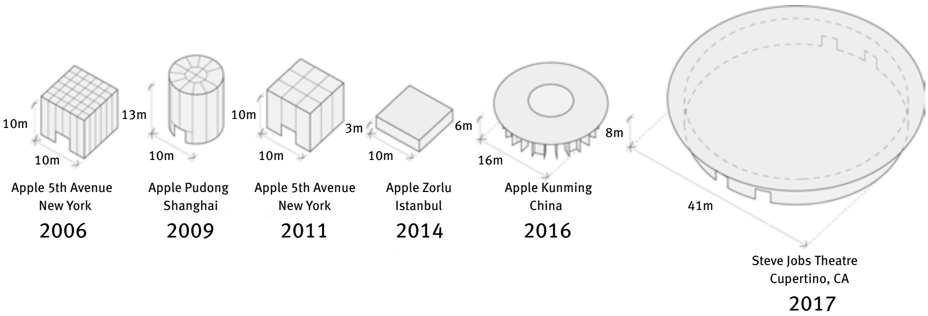

Fig. 4: Evolution of structural glass design.

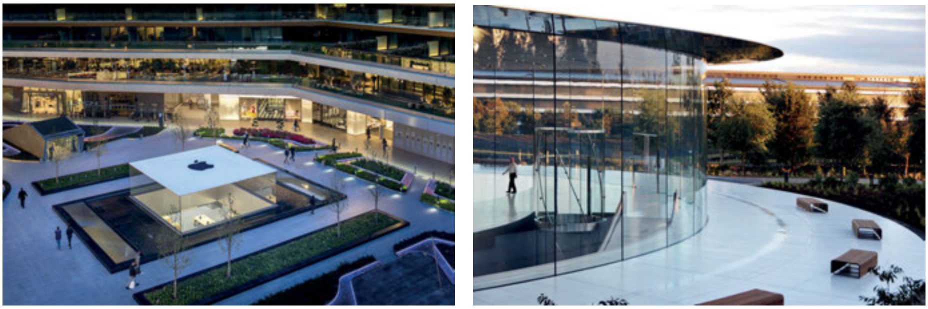

Fig. 5: Left: Apple Zorlu, Istanbul (Photo by Hufton+Crow); Right: Steve Jobs Theatre, Cupertino (Photo by James O'Callaghan).

the vertical and lateral stability of the whole envelope in a highly seismic zone. The glass panels are arrayed in a 41-metre diameter circle.

3 Glass as main lateral force resisting system

Foster and Partners' architectural and engineering teams developed the original concept alongside EOC Engineers. Working together allowed the team the opportunity to approach the design holistically.

The whole design team embraced the idea of pushing the glass design to its limit by considering the possibility of adopting unconventional structural solutions. This led to the use of the glass as the main lateral force resisting system being considered, without relying on more standard bracing strategies.

Glass is a brittle material. A structural glass failure could potentially lead to a catastrophic scenario if adequate countermeasures are not introduced. This is even more relevant when the glass is responsible for the lateral stability of the entire building.

Therefore, a detailed understanding of the structural behaviour of the dome superstructure was necessary in the early design stages. Several potential accidental scenarios had to be evaluated in parallel with the standard structural design in order to transform a given architectural concept into a valid structural scheme. This modus operandi led to the necessity of implementing the way we worked on each given architectural proposal by speeding up the whole analysis process.

Consequently, a systematic generative approach to the analysis process was finally considered to streamline our structural studies, hoping this would help facilitate working to an extremely demanding schedule. On the other hand, this choice was benefited by the proposed spherical architectural arrangement, possibly an ideal form to deploy this methodology.

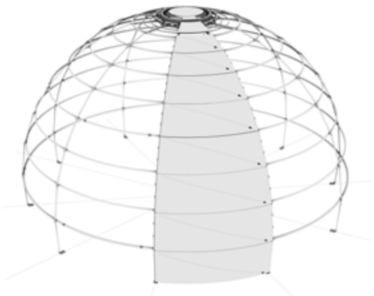

Fig. 6: Horizontal layout, system to resist horizontal loads.

4 Structural analysis and design: an iterative journey

Firstly, the dome superstructure consisted of a pure sphere, a relatively complex form from a construction point of view. Secondly, further complexity was added by the adopted panelisation scheme driven by the two following criteria:

- Maximization of transparency,
- Current glass manufacturing limitations.

Several architectural configurations emerged from the combination of these two criteria. Unavoidably, this approach did not necessarily lead to the most optimal structural arrangements. Thus, further detailed studies were required to transform a potential concept into a valid structural proposal.

Extensive studies were carried out in parallel on several schemes. Finite element analysis was performed with the intent of understanding the global structural behaviour under the imposed loading scenarios and estimating movements, natural frequencies and the level of stress in the structural elements. Special attention was then given to the buckling modes since the boost for transparency led to critically slender structural arrangements with a considerable number of elements prone to buckle. Each glass panel, which works as a tension and compression bracing element had to be checked for local buckling too.

Modelling had to capture the complexity of the details surrounding the glass and replicate the correct load path, which varied according to the analysed loading scenario. Different geometrical configurations had a strong impact on the required resources. Steel slender elements were conveniently approached as beam elements (1D), while the glass was generally approximated as shell elements (2D). Sometimes, brick elements (3D) were instead required to add granularity, but this was carefully balanced with the expected computational weight generated by the brick elements. Moreover, the supports in direct contact with the glass required special attention. Small structural elements called bearing blocks were used at the interface between glass panels; intermediate elements are necessary because glass should not come into direct contact with other glass elements. The bearing blocks have no tension capacity, hence, non-linear material analysis had to be performed, adding an extra layer of complexity.

Shear transfer between the glass and the steelwork was ensured through use of structural silicone, which could be modelled in different ways with appropriately associated computational weights. The first approach was to use springs (1D) leading to the creation of several elements spaced at intervals of between 50 and 100 mm. The second approach was to use brick elements (3D). Again, the choice of approach was based on computational efficiency. However, this led to geometrically complex 3D models, where a lot of extra smaelements had to be managed within a relatively large model in a short amount of time, increasing the risk of losing control over the model.

Before starting the analysis process, EOC Engineers' design team carefully evaluated various potential tools and software. Rhinoceros 5 (Grasshopper) and Strand7 R2 were selected as the main two software to create the global model and perform the required finite element analysis. The computational design workflow choice was based on experience and potential: Rhinoceros and Grasshopper gave us the possibility of generating and handling complex 3D models, while Strand7 R2 provided the level of detail we believe was required to tackle this project from schematic design to detailed design. Other tools were integrated, but with a minor impact on the analysis process.

The main challenge behind this strategy was the missing link between the two software. Drawing directly within the finite element modelling (FEM) environment was not feasible considering the complexity of the structural arrangement. On the other hand, importing models from the CAD environment into the FEM environment proved not to be a viable due to the tight schedule. It was essential to generate models within the CAD environment while preserving the freedom to manipulate them within the FEM environment. The Application Programming Interface (API) gave us the chance to establish a solid link between the CAD and the FEM environments. This synergy gave us the ability to bypass the FEM interactive environment and perform functions which were not directly available within the FEM software. This approach enabled us to streamline the analysis process, seamlessly generate options and variations and cope with the complexity of the structural glass design within a tight schedule.

5 Preliminary design options

At schematic design stage several architectural and structural schemes were analysed and assessed. This section aims to describe the challenges encountered during the finite element modelling phase of some of the options.

5.1 Geodesic layout

The geodesic arrangement tended to replicate a more traditional grid-shell structure with rather small panels. Glass manufacturing limitations did not allow for larger panels leading to a critical compromise in terms of transparency. Considering the proposed size of the building, an option with no steel superstructure was not a practicable one. A framing system had to be introduced and the reduced size of the glass panels led to a low glass to steel ratio.

From a modelling perspective the frame was approximated as beam elements, while the glass as shells. The glass provided lateral stability to the whole dome, and this was assured by a stiff interface between the glass and the steelwork. All local glass supports had to be included within the finite element model with adequate stiffnesses in order to reflect different materials, such as nylon or hard rubber. Each panel had up to twelve setting blocks. Special attention was also given to shear transfer and thermal expansion.

In the end this scheme was not pursued due to the lack of transparency and the difficulties to minimize the steelwork frame.

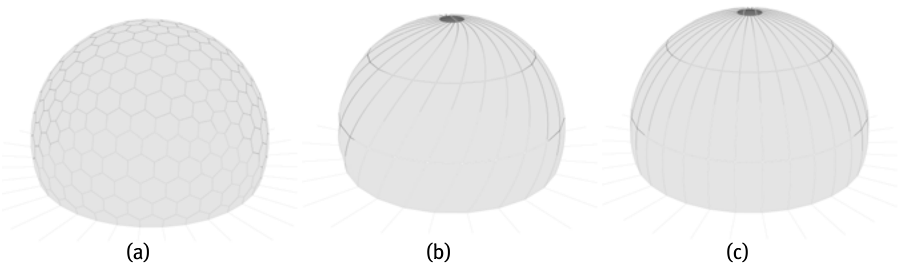

Fig. 7: Preliminary design options: (a) geodesic layout, (b) slanted layout, (c) vertical layout.

5.2 Slanted layout

In parallel to the development of the geodesic scheme, an alternative design with slanted glass panels took shape. The glass arrangement was characterised by long rhomboidal panels arrayed around the dome. This proposal took advantage of the glass manufacturing capabilities of the time leading to a higher degree oftransparency.

The glass panels were designed to be responsible for the lateral stability of the dome superstructure. A steel frame was added to restrain the glass and help transfer shear between the panels. Modelling proved to be challenging due to the complex panelisation and system to resist the lateral loads. Side setting blocks between the glass panels assured shear transfer at different levels and to the concrete podium.

Even though assuring a higher degree of transparency, this scheme proved to be too challenging for several factors including glass fabrication, installation and replacement. The structural system had to temporarily braced in case a glass panel had to be replaced. Thus, alternative options were investigated.

5.3 Vertical layout

A simpler version of the slanted scheme emerged where all panels were oriented vertically. This led to a simplification of the structural and geometrical arrangements. A slender steel frame had to follow the vertical glass joints to provide additional robustness to the system. This proposal proved to be simpler from a modelling perspective since the complexity linked to the glass local supports largely decreased.

However, the system to resist the horizontal loads did not benefit from the vertical orientation of the glass panels. While the structural scheme had some potential, the steel superstructure had to be increased to address buckling and frequency issues.

Ultimately, this scheme did not encounter the necessary support to be brought into the following stage and alternative options were investigated.

6 Final Design

6.1 Horizontal layout

The 30-metre diameter sphere was equally divided into 10 sectors and 9 gradually decreasing horizontal bands and completed by a 3.1 m diameter oculus manufactured as a single glass panel with a spherical curvature. This architectural arrangement led to the creation of an almost uninterrupted 3.2-metre tall transparent band at eye level. This was possibly the most optimal solution in terms of transparency as well as the glass manufacturing limitations of the time. The concrete podium was cladded with two additional fully fritted glass bands.

All glass panels between band 1 and band 8 were designated to be responsible for the lateral stability of the whole dome. These were supported on a slender steel frame organised in segmented mullions and circular transoms. Transom to mullion connections provided full moment continuity, while the interfaces between the concrete and the steelwork superstructure worked as hinges. Each glass panel was pre-bonded with structural silicone in the factory to two stainless steel conical plates along the top and the bottom edges. The glass was supported on bearing blocks for in-plane loads. The stainless steel plates were then connected to the steel superstructure.

All the structural elements mentioned above had to be included within the global model leading to a substantial drawing effort. The use of generative and parametric tools helped manage the geometrical complexity necessary to develop the full structural glass concept. All structural glass supports were generated and transformed into structural elements such as beam, shell and brick elements within the Grasshopper environment. The analysis process was also recalled within the Rhino-Grasshopper environment by using the Strand7 API. Adjustments based on the initial results were again performed in the Rhino-Grasshopper environment without the need to modify the model within the FEA environment. This approach helped optimise the whole analysis process.

Additional models were analysed in parallel to the main one in order to evaluate several potential accidental scenarios where some structural glass panels were alternatively removed and the ultimate behaviour of the dome superstructure examined.

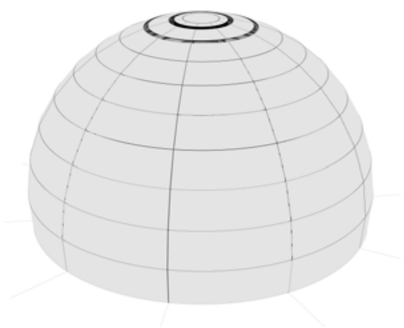

Fig. 8: Horizontal Layout.

6.2 The glass

All glass panels, except for the oculus, were conical in shape (singly curved with varying radii). This form represented the most optimal synthesis between the two leading criteria of enhanced transparency and glass manufacturing limitations.

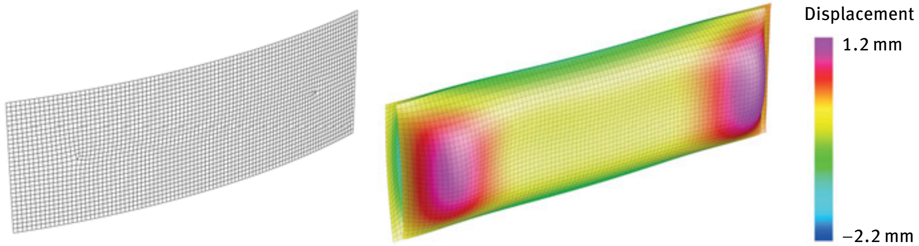

Fig. 9: Horizontal layout. Deflection under climatic loads, detail of local FEA model.

The conical shape was achieved through the cold bending during lamination manufacturing procedure (sometimes also referred as warm bending), where the individual glass plies were forced into shape on a mould prior to lamination with the ionoplast interlayer. After the lamination process, the glass mantained its conical shape thanks to the shear strength of the interlayer.

Modelling of the glass panels was carried out globally and locally. A local model of each conical glass panel was generated to simulate the bending process and estimate the expected spring-back when the panel would be released from its mould. Due to the conical nature of the geometry, spring-back varied across each panel.

Detailed models of the conical panels were also used to evaluate the level of stress in the insulated glass units (IGU) caused by climatic loads, such as variation in pressure and temperature.

The *oculus,* placed at the top of the dome, was the only spherical panel. It was manufactured differently from all the other panels due to its doubly curve form. It was slumped and then laminated with ionoplast interlayer.

6.3 Modelling approach

The structural modelling began with a simplified stick model. This helped build confidence in the global scheme and created the basis for the subsequent modelling strategy. The latter was characterised by some calibrated steps aimed at reducing the gap between the digital and the physical environment by adding complexity without losing control.

Modelling progressed in a few steps:

– The glass was incorporated into the global model as plate elements with simplified connections between the glass and the steelwork.
– A conical door was added within a sector at 'ground' level (band 1). This generated an asymmetrical weakness that required local strengthening and two additional mullions next to the opening.
– Further detail was added to the glass to steel connections, including silicone patches, toggles and stainless steel clamps that helped restrain the glass panels

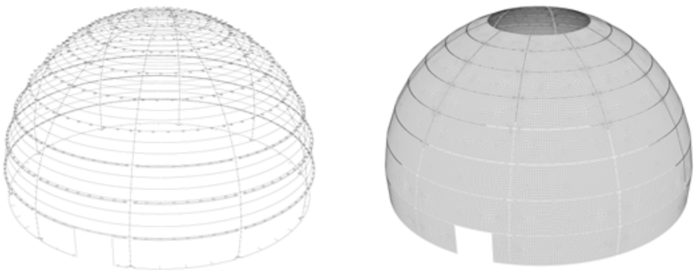

Fig. 10: Left, horizontal layout. Detail of FEA model, with beam elements, right, horizontal layout. Detail of FEA model, with beam and shell elements.

in and out of plane. At this stage all additional items were modelled as beam elements.

– All glass supports were later modelled as plate elements. Local 3D brick models of the glass to steel connections were generated in order to evaluate the level of stress concentration in the glass panes at each connection.
– Construction stages and accidental scenarios that simulated potential patterns of glass breakages were investigated in parallel.

The chosen generative approach helped retain control over a global model which was eventually characterised by a high degree of complexity. Global and local models were developed within the CAD environment and analysed in the FEA environment. Results were then retrieved in the CAD environment using the application programming interface. This process also helped calibrate the model during the various design iterations and construction stages. Cross-sections, materials properties, units and loads were all defined and directly controlled through components in Grasshopper, visualisation of all the results was also managed in this environment.

6.4 An alternative structural approach

An option based on local mechanical fixings for shear transfer between the glass and the steelwork was explored as a potential alternative to the use of structural silicone. The glass had to be manufactured with holes in order to ensure shear transfer to the steel superstructure throughout stainless steel bolts.

Modelling proved to be more challenging than any other option due to level of detail required by each mechanical fixing point, where the interface between the glass and the steel had to be modelled thoroughly. Several mechanical fixings were placed along the top and bottom edges of each glass panel at a distance of 50 cm. Each bolt had to be surrounded by either grout or nylon to resist in-plane loads and capped with machined stainless steel washers for out of plane loads.

In the end, due to the complexity of the joinery system and the high level of stress concentrations in the glass around the mechanical fixings, this option was discarded.

7 Results

While the use of the API undoubtedly helped optimise the modelling and analysis process, a significant amount of time had to be spent to adequately manage the link between the CAD and the FEA environments.

Several levels of control had to be introduced to thoroughly check the whole digital workflow. This helped expand our experience and give the senior members of the team the right level of confidence to endorse the proposed structural design.

We can affirm that, even though some challenges had to be faced, the team unquestionably benefited from the approach described in this paper.

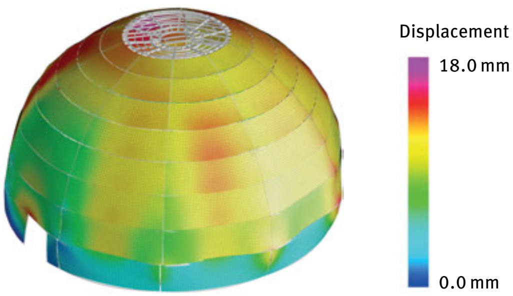

Fig. 11: Horizontal layout: Deflection under wind load.

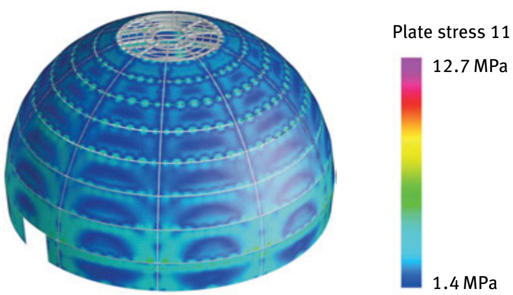

Fig. 12: Horizontal layout: Principal stress 11 in the glass elements, ULS envelope.

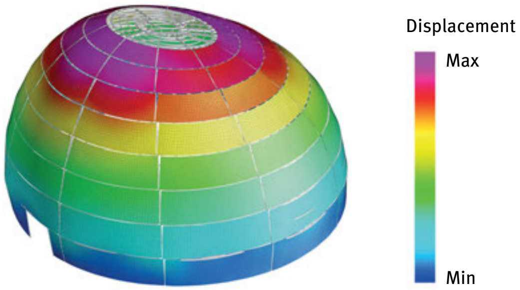

Fig. 13: Horizontal layout: Natural frequency analysis, first mode 2.1 Hz.

8 Manuscript Reflection

It was the first time that we adopted the use of the API for a such high-profile project. Even though it was considered a success, this methodology was questioned several times internally due to the tough challenges we encountered, especially at the very beginning of implementation.

It should be noted that the spherical architectural arrangement facilitated the application of the API strategy. On the other hand, the complexity linked to the glass structural design posed arduous challenges.

We can observe that some design stages were more appropriate than others to exercise this methodology. Schematic and detailed design proved to be the most efficient ones. During these two phases the number of options to be evaluated was narrowed down to a small group, while an adequate level of detail was required to give the whole team the right degree of confidence to proceed.

There are no doubts that this approach will be applied again in the future, but not all projects are suitable for this. The experience gained through the analysis and design process of the dome superstructure will guide us to decide when to adopt this strategy for any future applications.

The designers of Apple Marina Bay Sands pushed the boundaries of the industry in favour of lightness and transparency [8]. The latest advances in the glass manufacturing industry accompanied by the integrated analysis method outlined in this article helped develop a structural system that responded to the given challenge.

The project leaves us with the next frontier on the horizon. At the time of writing (May 2023), no manufacturing technology has advanced to produce doubly curved spherical glass panes at the same scale of the conical ones utilized. However, supposing the manufacturing technology was possible, what would be the structural as well as optical challenges that may result from the development? How would these benchmark against systems that provide more conventional load bearing systems and materials? These questions suggest further investigations.

The desire for lightness and transparency is far from over, and, as designers, we now face even bigger challenges, such as sustainability, logistics, limited resources etc. Based on the experience gained on this project, a further integrated structural design process could benefit the development of the design of any future challenging project.

9 Conclusions

In conclusion we have explained the challenges and introduced a method to integrate and interactively design and analyze spherical glass structures utilizing the glass itself as main lateral force resisting system. We have tested the method through the iteration of several options and variations and could therefore evaluate the benefits or otherwise of these that culminated in the manufacturing and construction of the chosen structural typology. Finally, the manuscript provides a reflection upon the methodology and provides a reflection for further investigations.

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