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Planning Phases of Glass Projects

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Abstract

This paper showcases the challenges in design, fabrication, and installation of glass projects. The modus operandi of an engineer working with glass is presented and the rationale behind the decisions explained. The first section discusses the motivations in several projects. The life cycle phases of the projects are outlined. The second chapter introduces the importance of conceptual design and generation of options on an all-glass staircase project example. Communication of the design intent is outlined in the third chapter, supported with graphical communication extracted from our recent project of a feature wall and glass elevator. The paper concludes with a brief discussion on procurement and construction phases with primary focus on the recently finished Coal Drops Yard in London. Final remarks on the structural glass design experience are presented in the conclusions.

Keywords

Glass, Planning, Projects, Design

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1. The Project Phases

Exciting projects are naturally starting their lives in competition workshops where ideas flow effortlessly. At the early competition stage, proposed concepts are bold, unsurprisingly to catch the eye of the judging panel and the attention of clients. Teams aspire for the differentiating aspect to distinguish their project on the market from many others. Good understanding of the basic design principles learning from the past development while also researching new trends is robust principles we adopt during the conceptual design. Ideas of circular economy and reuse of existing materials are at the forefront of our research. Because an opportunity presented itself to retrieve single-layered glass panels from one of our current refurbishment projects, we explored the conceptual idea of how to re-purposing architectural glass. The concept of historical double framed timber windows with each leave being single glazed combined with an active desiccant system was explored in this study as presented in figure 1.

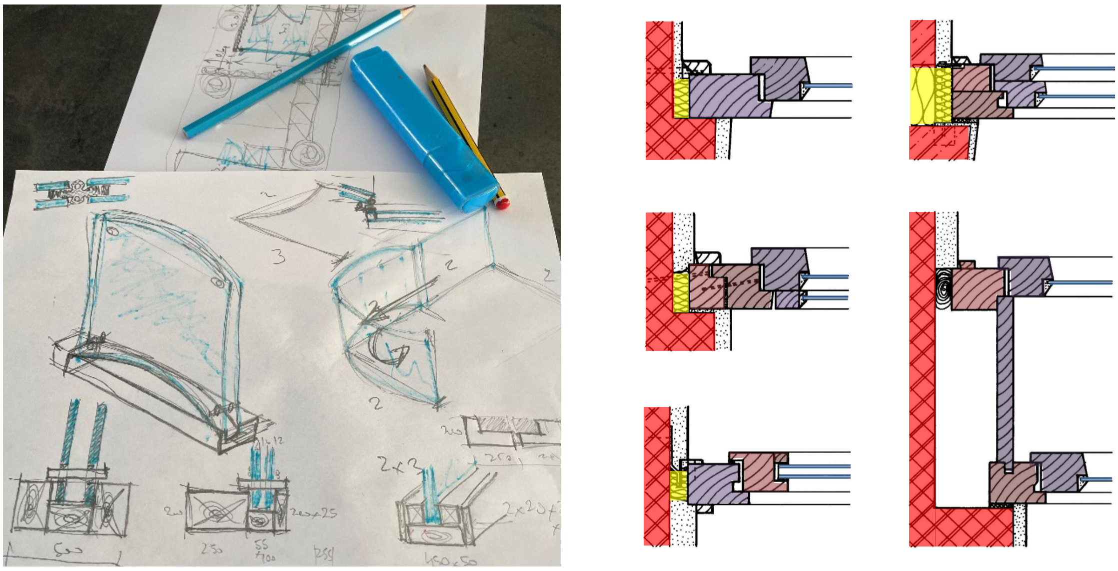


Fig. 1: Conceptual design

Figure 2 presents the architectural model of Coal Drops Yard, King's Cross. This project is part of the largest mixed-use development developed in central London for over 150 years. King's Cross is a vibrant new city quarter of offices, homes, community facilities, university and a host of shops, restaurants, bars, and cultural venues. The new anchor point building with expressive architecture to capture attention and give character to the plaza reflects its dynamic surroundings.

Developed by Argent with architectural concept and execution from Heatherwick studio, and engineering support from Arup (Bateman et al. 2019) Specialist glass contractor Frener & Reifer fabricated and constructed a complex structural glass facade.

Fig. 2: Coal Drops Yard, architectural model

Design stages are often perceived as spanning over multiple years where projects might stop and start while being redesigned or altered to meet new requirements from the client. Further years of the actual construction phase are added to the design phase, encapsulating performance testing, mock-ups and finally fabrication and installation. However, the life of the project is not ending with practical completion, on the contrary, it is just starting.

Phases of project life:

- Competition
- Design
- Construction
- Grand Opening
- Teething problems
- Midlife crisis
- End of the life
- Refurbishment or Demolition

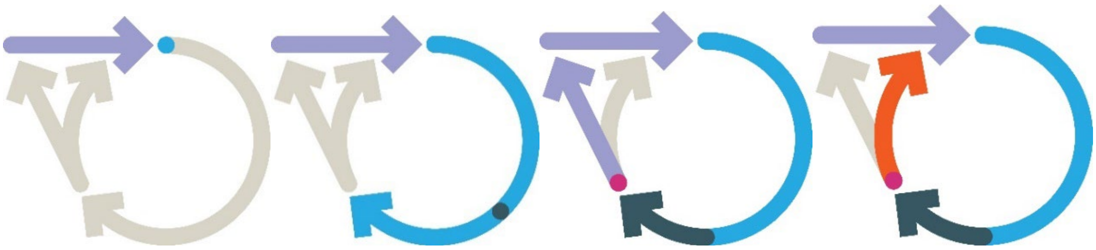


Fig. 3: Project life cycle phases diagram

Building performance in the initial years of operation is key to the occupants, where initial problems with performance might be revealed. Building pathology and failure investigation can include controlling the immediate impact, investigation of the failure, remediation and advice on settlement costs and expert advice. A decision point is reached at some point in the lifespan of buildings on what to do with the assets. How can the building's life be extended, keeping it in the circular economy? In our office, we developed the design expertise to take existing structural glass projects and design a new function or extend service life. We can coordinate energy performance and comfort models and propose suitable small-scale interventions extending the project's life or recommend strategic large-scale refurbishments if necessary.

2. Conceptual design – Scheme and Ideas

As discussed earlier, sustainability and circular economy are presently the key drivers in our designs. We are examining the embodied carbon of a variety of typical materials and facade systems. Glass has relatively low embodied carbon, while metallic materials have higher embodied carbon due to their energy-intensive production. We aim to reduce material use where possible.

Additional fabrication processes of~~-~~annealed glass such as heat treatment, heat soaking, lamination, edge polishing, and the coating can more than double the embodied carbon footprint of the final product. However, it is expected that these processes will improve product performance, decrease glass thickness, and reduce operational carbon footprint.

In addition, we have been researching (DeBrincat & Babic 2019) the existing linear take, use and dispose, mentality of the architectural glass industry. The short service life of hermetically sealed insulated glass units against the indefinite life span of the glass itself is a problem that needs solving. Much of the glass currently removed from buildings end in landfill or low-value aggregate products but this could be collected and input into the manufacture of float glass. This could see a significant reduction in CO_2 emissions, finite resource use and landfilling from glass manufacture. Our pilot project in refurbishment of the Burrell Collection Museum completed in early 2022.

2.1. Project example – "all-glass" floating stair

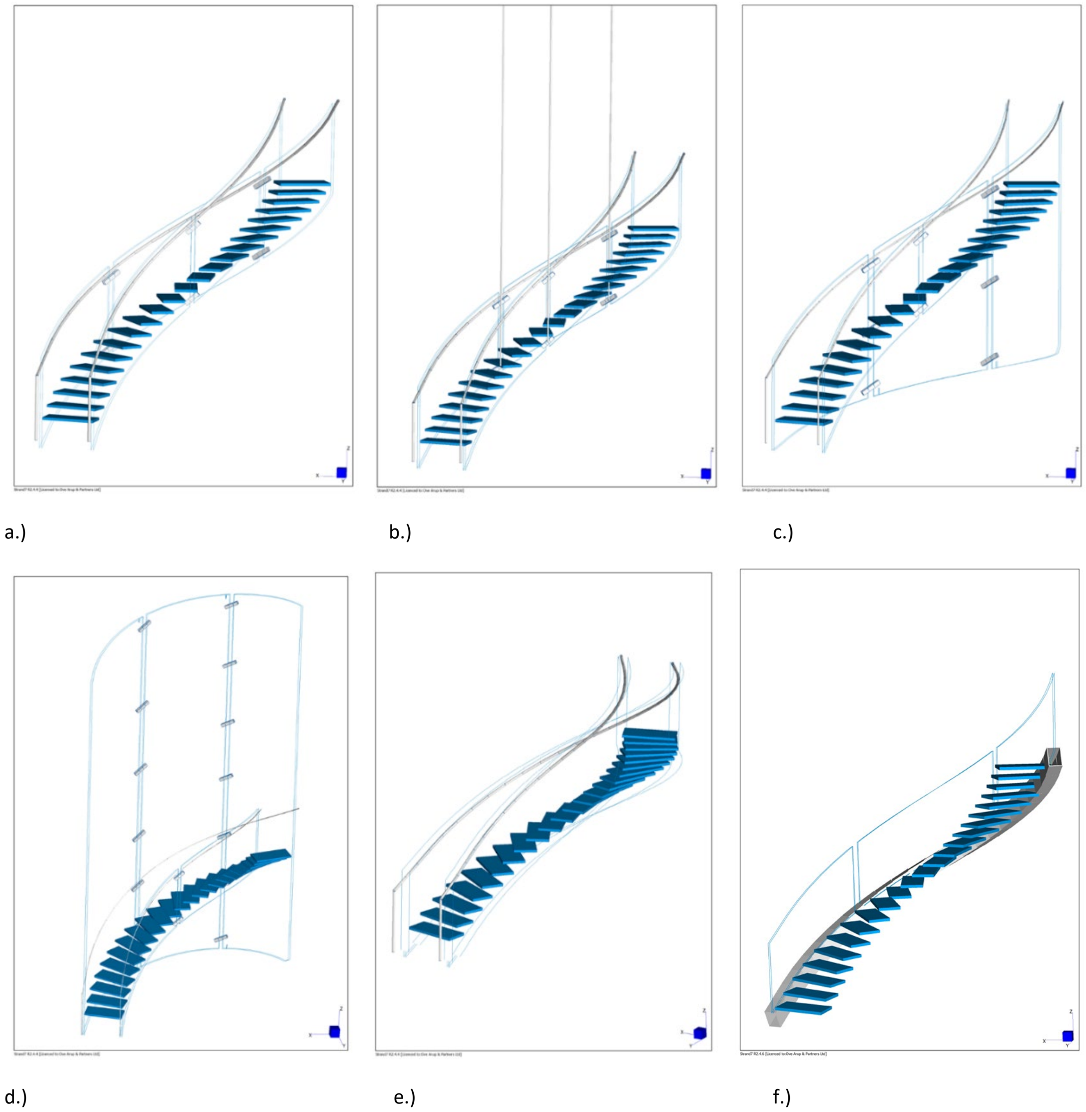
Glass can be used in many structural systems as one-dimensional beams, two-dimensional plates, or three-dimensional shells. In our team, we often develop multiple options for each commission at the concept stage to give our clients a range of alternative schemes to select from. We developed schemes in Figure 4 for the project of an all-glass spiral staircase, where multiple choices were presented to our client. Project location is confidential. For each option, we summarise the pros and cons, and we evaluate the performance and cost prospects.

Because of the length difference between inner and outer stringer, asymmetric bending and torsion need~~s~~ to be resisted by the structural system. In Option 1, we stitched together curved glass panels with stainless steel straps into a continuous glass beam. Glass treads will have to act as in-plane ties – to make a Vierendeel frame. This will need thorough structural verification and detailing with performance testing. Structurally, this is a highly integrated option where all components are fully engaged.

In Option 2, we vertically hung curved glass panels with stainless steel rods. Stainless steel rods will require a separate stiff structure in the roof. We could design glass treads as simply supported elements, but they will still need to act as ties/props between both stringers. In-plane Vierendeel action will not be required which is a significant simplification from the base Option 1.

In Option 3, curved glass panels are stitched together via stainless steel straps into the continuous glass wall. This solution could offer improvement in the structural performance and the dynamic response. We propose the outer stinger as the bottom supported glass wall, while the stiffer, shorter inner stringer can remain as a glass beam as designed in base Option 1.

Option 4 is structurally similar to the previous Option 3. The benefit of the integration of an external glass facade with a stair was explored. A potential complication might be additional loading from wind load and possible seismic movements accommodation in this hybrid system.


a.) b.) c.)

d.) e.) f.)

Fig. 4: Glass stair concept design options
a.) Option 1 - Structural stringer, b.) Option 2 - Hung glass stringer, c.) Option 3 - Glass wall,
d.) Option 4 - Integrated stair with façade, e.) Option 5 - PMMA with casted site joints,
f.) Option 6 – Glass and steel stringer,

In Option 5, curved PMMA panels, approximately 150mm thick were investigated. We proposed to adhesively connect panels in situ into the continuous beam. Acrylic joint strength and reliability will be critical for this design. Location of the joints and shape of the joints with shear keys can significantly improve connection performance. No visual steel connections are needed as the handrail can be a simple groove in acrylic. Glass treads will have to act as in-plane ties—Vierendeel frame. While following the architectural intent, with seamless joints and floating appearance, the PMMA option will likely be the heaviest one, as the thick build-up is required to meet structural requirements. This will also make it more expensive compared to the other options. The scratching resistance of acrylic is less than that of the glass, but repolishing is possible. The challenge of UV resistance will not be an issue for an internal stair.

Option 6 is a more traditional steel and glass option, with a torsionally stiff fabricated steel box stringer and cantilevering glass treads. This alternative proposal will meet partially desired architectural intent. It will be the most economical option with the possibility to open for a local procurement route.

Testing of innovative systems like all-glass stairs is an integral part of the design to verify performance and requirements. The testing should follow appropriate local guidance and meet the local criteria. If there is no such guidance, we propose testing to international standards or alternatively testing procedures could be developed to capture project-specific requirements. There needs to be a sufficient allowance in the programme to allow for testing to take place and verify the design. It shall be noted that design verification cannot exclusively be based on testing, especially if only a few samples are tested.

Example of project tests considered:

- Connection testing
- Component testing, treads, balustrade impact
- Performance mock ups of assemblies,
- In situ load test on as-build structure
- Slip resistance testing

Glass structures are rather complicated and therefore require advanced project management procedures. We recommend drafting a design risk matrix from the early stages which enables designers to capture items that should be developed or solved in the next phases or if critical information is missing. The intent of this risk matrix is to be a live document, with the items being open and closed, as the design and construction progress. Ultimately this document will be handed over to the specialist contractor at tender stage to inform tenders on past decisions. After thorough reconsideration of all pros and cons Option 6 was selected and currently the staircase is under construction with projected practical completion in 2022.

3. Communication of the design intent

In complex systems, clarity to convey design intent to our technical and non-technical collaborators is of utmost importance. Sketches, models, and drawings need to be understood readily but also bear necessary performance information. We expect that connections are capable to safely transfer load and accommodate fabrication and installation tolerances. A simple sketch to show an initial idea is naturally the best communication tool at the early stages of the project. We then develop selected ideas through consequent design phases to the construction details.

We selected one of our most recent projects, Atlantis, The Royal (location is confidential) which comprises two internal glass feature elements. In this project clear communication of the design intent and detailing are key for the project success. The lobby is water-themed and is flooded with light with views across 2 major external water features to the beach with the city skyline in the background.

3.1. Feature double skin glass wall

The first element is double skin feature glass walls, where interior designers were looking for the minimum expression of structure. Each wall is 6,650mm wide by 10,450mm high. With water running over the glass surface, precise fixtures and jointing were critical to maintaining a smooth flow of water. Materials need to withstand conditions that will arise during the operation, particularly water at the internal skin in combination with a cavity fire feature. The real fire feature in the cavity of the double skin wall will need to be a fully sealed combustion chamber.

We will concentrate only on the option selected for the construction. Following the scheme design review, the wall comprises 3 full height panels. This was to ensure an undisturbed water flow on the face of glass, which would be more challenging if horizontal joints were to be introduced. The full height structural glass option is base supported on a steel transfer structure to mitigate substructure movements. For similar reasons we disconnected the top of the glass wall to provide self-stabilisation of the glass wall for the in-plane direction via structural silicone, a set of bearing blocks and glass shear wall action.

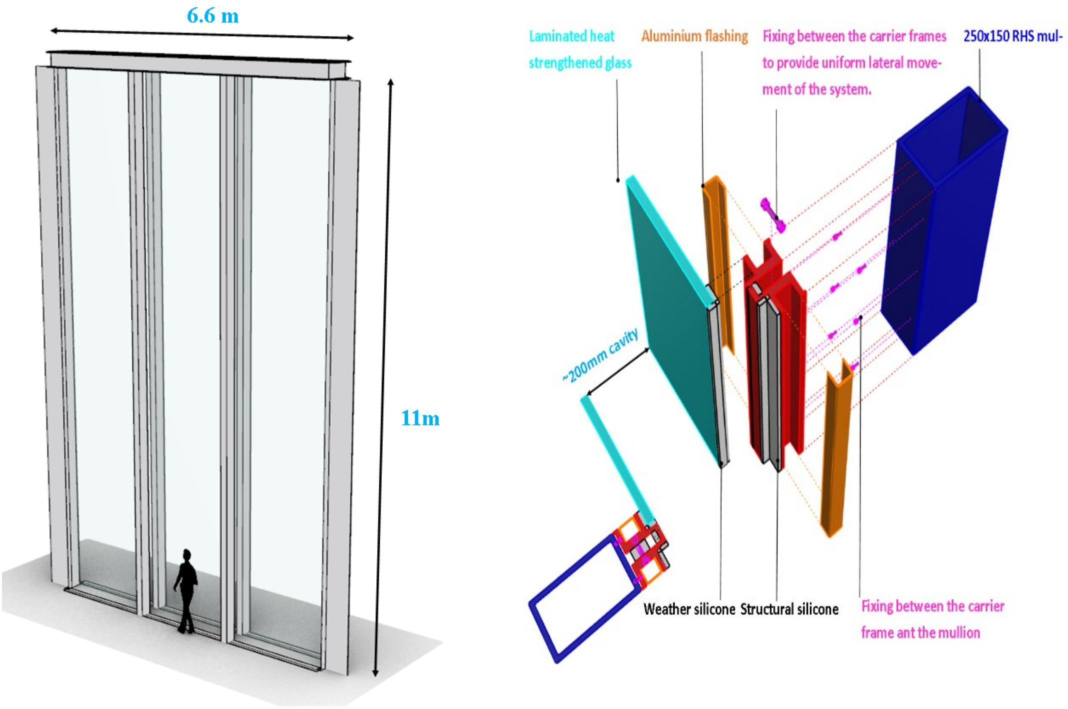
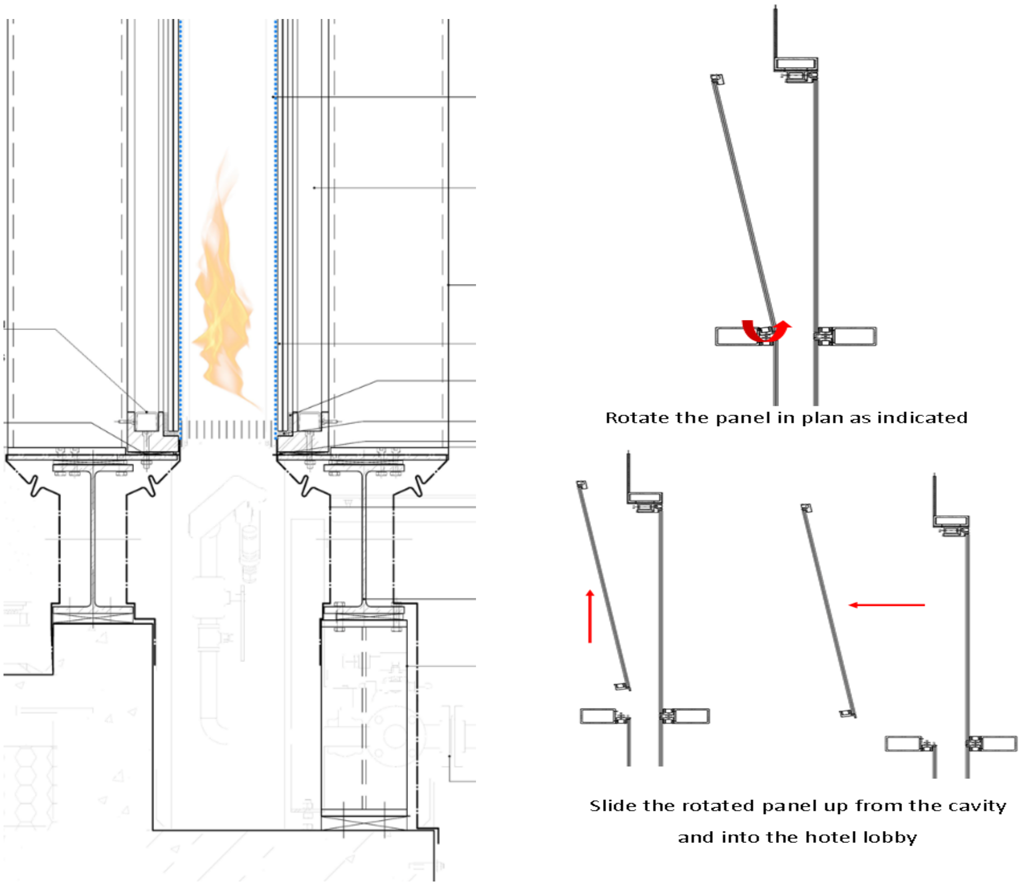


Fig. 5: Left Feature glass wall concept, right exploded detail of the typical connection

The panels would need to be bonded before erected, to ensure a smooth, flush joint between panels in the cavity space. We require this to ensure unobstructed and continuous water flow evenly over the surface. The vertical joint will be challenging to seal around the combustion chamber. This is of utmost importance from a safety perspective to prevent the leaking of CO and other gasses from the cavity into the lobby space. We bonded the carrier frame on the glass of-site and are providing the first line of defence from smoke and water between the wall and the hotel lobby.

We accommodate the differential movement between the primary structure and consequently the frame of the wall and the glass in the connection between the carrier frame and steel frame mullions. This is where the secondary system of gaskets is introduced in order to prevent the leaking of gasses into the lobby. We achieved this with a butyl bed applied around the fixings. We advised to pressurise the cavity between the frame and the carrier frame while the gas burners are active. This is to prevent the leaking of gasses into the lobby because of the pressure differences in the system. We propose this measure because the environment in the cavity while the burners are active was unknown at design stage.

Figure 6 illustrates the fabrication and installation challenges of envelopes comprising 11m long glass panels. The installation sequence and space required to manoeuvre such panels need considered throughout the design. The installation and replacement strategy is such that the carrier frames for glass panels are individually attached to the mullion frame. We also attached the carrier frame at the top and bottom edges to the mullions, spanning freely in-between them. This way the glass can be unscrewed from the mullions, slid into the cavity, rotated in plan, and slid out into the lobby. Glass is fitted with a carrier frame, which is bonded to the glass in a factory. This will help with airtightness and tighten tolerances and performance because of the increased quality control.



Rotate the panel in plan as indicated

Slide the rotated panel up from the cavity
and into the hotel lobby

Fig. 6: Left Bottom detail of the feature wall, Right Installation, and replacement diagram

3.2. Feature all glass elevator

The intent for the glass lift enclosure was to provide a minimum expression of the structure and lift guide rails. The lift is the second part of the same commission. The design concept of water cascading over the external glass surfaces requires precise fixtures and joining to maintain a smooth flow of water.

Connection points of the guide rails are to be placed at 1.4m centres. This was comprehensively discussed with the lift supplier to minimise the guide rail profile. The diagrams in Figure 6 illustrate the geometry of the feature all-glass lift. The lift provides access between 2 adjacent floors which are approximately 8m apart. The lift is roughly 2.8 meters in diameter and is divided in plan in 60-degree sections. Five up to 11-meter-long glass sheets are used while the door ribbon was formed from the metal panel. The possibility to reduce the lengths of the glass panel to finish at the ceiling was adopted. Because of the water introduction zone, a flush metal ring beam has to be introduced at top.

The 'All-glass' structural option was selected after scheme design review. This option comprises 11 meters long pieces of laminated glass, spanning the full height of the lift. There is no visible steel structure, other than the connection points and brackets. We partially hid these connections from view with detailing. We need a ring beam to stabilize the structure for horizontal loads (i.e. to make the glass work together from a structural point of view).

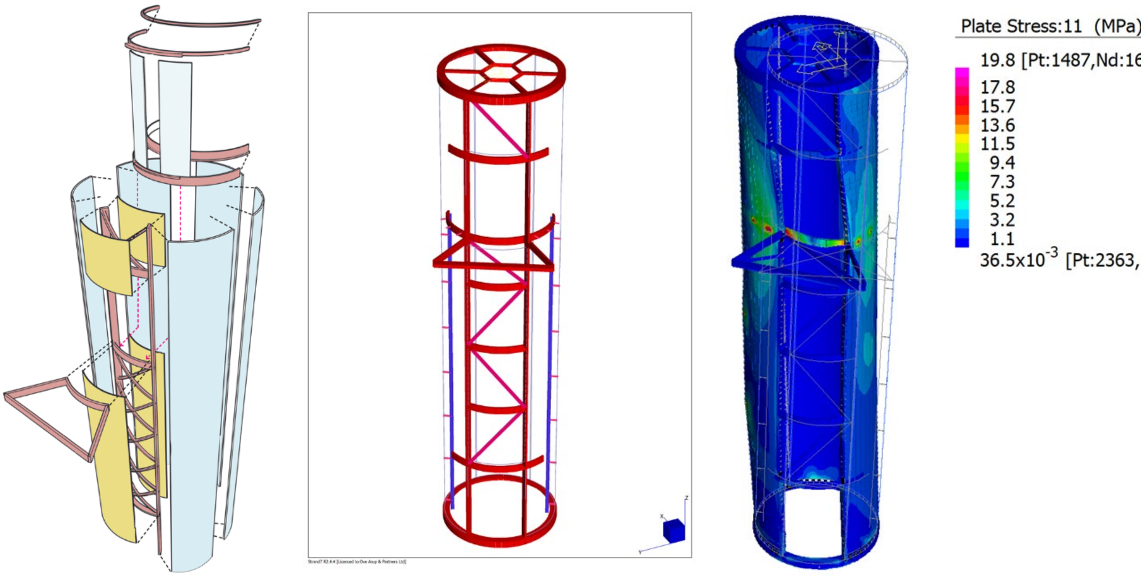


Fig. 7: Left - All glass lift, Middle -Structural model, Right - Analysis results glass stress

All the dead load, bar the weight of the top door and the glass above it, is supported in the bottom slab. This introduced some high point loads, which needed to be considered in an early stage. The joints are to be filled with structural silicone, which has a preponderant role in the overall structural performance of the lift.

Because of the large glass size, the cost of this option is the highest. The number of suppliers capable of producing glazing of this size is very limited. The continuous outer surface of the glass provides the optimum surface for a smooth and continuous water flow.

We aimed to minimise structural movements since the stiffness of the glass tube is significant. We detailed connections to not transfer additional loads from the primary structure. We proposed each glass panel to be supported on a rocker detail at the centre. We detailed first-floor landing beams to allow for vertical and inter-story drift movements.

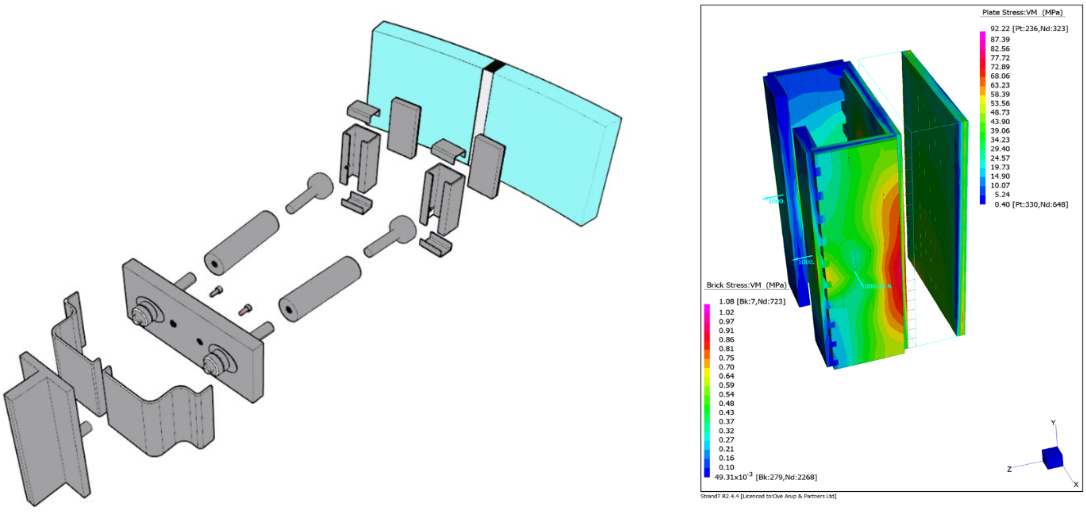


Fig. 8: Left- Connection exploded diagram, right- FEA analysis of adhesion connection

The main requisite for the connections is to sustain and transfer safely the reaction loads of the lift cars. We identified two viable options at this stage:

- Continues carrier frame option
- Point fixed option with transparent structural silicone

The point fixed option connection with transparent structural silicone was selected and executed. We minimised the width of the connection to reduce challenges in fabrication because of the bonding to the curved surface. Both projects are currently under construction by specialist glass contractor, Seele, with completion date second half of 2022.

4. Procurement & Construction

We expect an engineer to deliver the first reality check to the project. Glass as a raw material is relatively inexpensive, material cost is added in processing and risk margins. Glass has a cost range of £500 - £5000 per square meter dependent on its application. It is often very difficult to identify added value and boundaries of acceptance. Early agreement between key stakeholders is essential. The cost of glass structure is often non-linear, where relatively insignificant changes in design may increase the cost. Adding manufacturing processes or increasing sizes may lead to a long lead time or costly handling and installation difficulties. Some projects currently in construction phase, we were fortunate enough to collaborate, are shown on figure 9 below.

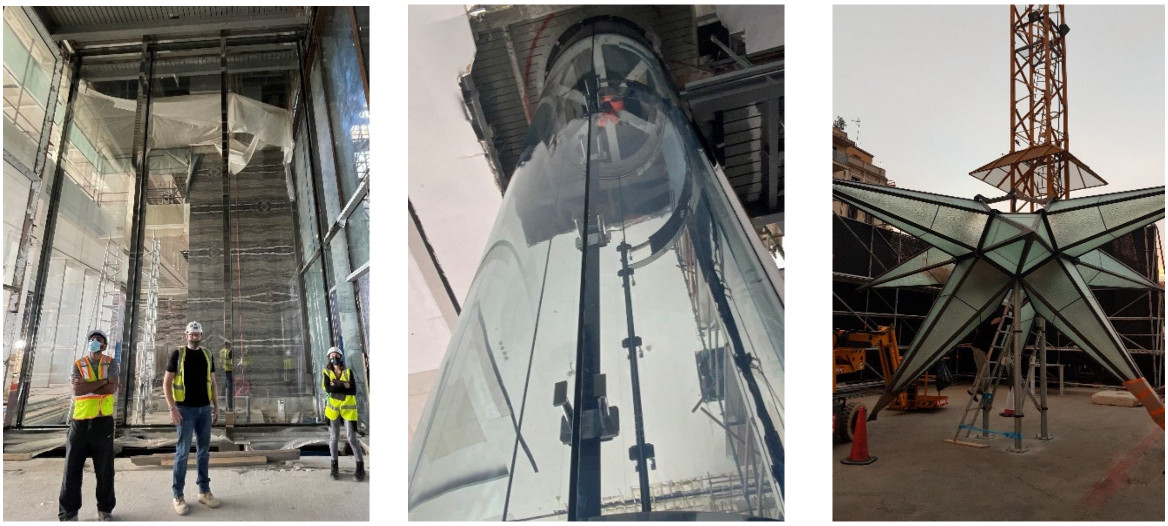


Fig. 9: Construction progress, Left - Feature wall, Middle - All glass elevator, Right – Glass star,

4.1. Coal drops yard

We employed sophisticated engineering principles combined with extensive experience within the glass industry to deliver a remarkably bespoke structural glass solution for the 8m tall glazed facade. The general description of the project was given in Chapter 1 of this paper, with project pictures in Figure 10. Our design uses the full capabilities of structural glass. Using the serrated geometry, each piece of glass supports its neighbour. The returns act like fins to support the larger pieces, following principles of folded plate systems. We researched origami-like structures (Griffith et al. 2016) hybrid glass structures (Lenk 2017) and the behaviour of structural silicone (Noteboom et al. 2020) extensively in past. Because of this work, we gained confidence in such innovative systems. We proposed it to our ongoing project, which enabled us to further extend our understanding of the subject.

Fig. 10: Left - Finished façade, Right – Project during the construction of the primary structure

Structural silicone is well known in the facade industry with an excellent track record. In recent years, the industry came through material science transformation, where new material models were developed (Staudt et al. 2018) to predict structural behaviour. First principles analysis is always performed but numerical models help to justify most complex designs. We used structural silicone for the connections,–which provides weather and airtightness and structural support. Vertical glass connections transfer axial and shear forces only. The design is fully optimised, and we used the glass both for enclosure and structure.

Silicone bonded structural glass walls are susceptible to structural movement of the primary structure, which was relatively difficult to comprehend because of its complex nature. One of the key challenges in any building envelope is to develop a convincing strategy to address movements and tolerances. With the primary structure of varying stiffness and such complexity, it required multiple iterations and detailed discussions within the design team. In the initial stage, we investigated various options, where base supported panels with a central rocker were selected as the most appropriate solution for this scheme. We support each glass panel on the central rocker which transforms bending deflections of the primary structure into vertical movements in joints between glass panels. Horizontal drifts, as well as vertical deflections occurring after the glass walls are connected with structural silicone will stress those joints. Permanent stresses in silicone joints are unacceptable and therefore a sequence of silicone installation was agreed upon. The specialist contractor took on this challenge and thoroughly analysed silicone joints for multiple load combinations.

We came up with a design that utilises the glass fully, making use of the serrated geometry to support each large piece of glass to the other. The return panels work as supports for the larger front elements, just like fins in traditional structural glass arrangements. The connection between each piece of glass is through structural silicone, making the design completely integrated. We used the same material for structure as for enclosure and use silicone for weather, air tightness and structural support. There is nothing redundant, no metal fittings are used.

In the structural glass, connections are the most important aspect not just from a structural perspective but architecturally too. From the early stage, we added connections to the design meeting agenda. The client and the design team appreciated the early involvement of a specialised contractor. Hand samples helped visualisation and convinced our partners about the buildability of such an innovative scheme. We presented a full range of connection typologies from bolted to laminated titanium insets. Soft adhesives are more beneficial as stress distribution in glass is more uniform and joints can accommodate movements.

Fig. 11: Left- Hand mock up of connection, Middle – Visual mock up, Right – Project during façade installation

With high-end projects like this, early contractor engagement is very important. Figure 11 (left) shows a mock-up which the contractor carried out for the Client to show the contractors determination for the project even before being officially appointed. We typically engage with contractors very early on, to understand the current manufacturing limitations and how willing they are to push the boundaries. Importantly, engaging early allows us to manage the expectations of all parties involved and helps to understand and control cost carefully. Free-form architecture and high complexity in heritage protection in the heart of London required an integrated and collaborative approach in the early stages.

We constructed the mock-up at Frener & Reifer HQ in Bressanone, Italy depicted in Figure 11 (middle). Early contractor engagement allowed mitigation of risks and reduction of uncertainty. The BIM environment guaranteed effective coordination throughout the entire project development, ensuring time, costs, and quality control. In complex projects, a collaborative effort between the architect, engineers and contractors delivers unique facade systems underpinning the architectural concepts.

5. Conclusion

The life of a glass project is certainly not a trouble free one. Many challenges are waiting ahead, which can de-rail or terminate initial concepts during the early design stages. Sustainable design pressures, risk adverse clients, uncertain economic future, or contractor’s ability to fabricate and install proposed schemes can be named as key contributors. It is always time to celebrate when after years of computer simulations, drawings and design meetings, the first visual mock-ups or the site installation progress report are presented. This paper is part of these merriments, where the solid effort of all collaborators is acknowledged.

Acknowledgments

My sincere thanks to all my colleagues, clients, collaborators, and contractors who have helped us with our past, current and future projects.

References

Bateman, S., et al.; A Victorian heritage site adopted for 21st-century London, In: Arup Journal VOL 54 Issue 2/2019, p.4-13, London, UK, 2019

DeBrincat, G., Babic, E.; Rethinking the Lifecycle of Recycling Architectural glass, In: GPD Glass performance days 2019, p.267-272, Tampere, Finland 2019

Griffith, J., et al.; Structural Analysis of folded Glass Plate Structures, In: Challenging Glass vol. 5, Conference on Architectural and Structural Applications of Glass, Belis, Bos & Louter (Eds.), p 39-48, Ghent, Belgium 2016

Lenk, P.; Hybrid glass structures, GPD Glass performance days 2017, p.90-94, Tampere, Finland 2017

Noteboom, Ch., et al.; Complex curved storefront: The Looking Glass. In: Challenging Glass vol. 7, Conference on Architectural and Structural Applications of Glass, Belis, Bos & Louter (Eds.), Ghent, Belgium 2020

Staudt, Y., Odenbreit, C., Schneider, J. Failure behaviour of silicone adhesive in bonded connections with simple geometry, Int. J. Adhes. Vol. 82, Pages 126-138 (2018)

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