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Designing with Structural Glass

P. Lenk
Arup, UK, peter.lenk@arup.com

Glass has been in existence for more than four thousand years. Techniques of manufacturing and design have since been under constant development. Today, we face new opportunities and challenges with respect to structural glass applications. This paper will explore objectives as to why glass is specified on building projects and outline key parameters which must be considered when designing with structural glass. A holistic approach and emerging design and construction techniques such as digital design, multi parameter optimization techniques, bar coding of glass, additive manufacturing and the potential of Building Information Modelling (BIM), will be discussed. Lateral thinking and examples from other industries will be presented and the paper will be briefly summarized.

Keywords: Structural Glass, Design methodology, Holistic design

1. Glass Qualities

1.1. History

Glass is created when molten material cools so rapidly that there is not enough time for a crystalline structure to form. Rocks with glass-like qualities were formed as a result of the intense heat and pressures created by meteoritic impacts. Our ancestors found these rocks intriguing; particularly the transparent quality the material exhibited. Small items of jewelry, such as earrings containing natural glass stones, were discovered by archeologists. There is no doubt that such objects were made with a more subtle method, rather than the result of a meteorite impact. .More practical applications of natural glass were also discovered; the hardness and mechanical strength of the material was utilized to create objects such as obsidian hunting spears and blades, (Fig. 1a). It is clear that from very early days, glass was considered as both an aesthetically pleasing and practical material.

Some thousands of years later, our ancestors discovered the art of mixing the right proportion of sand, soda, and lime to create artificial glass. The artisan quality of glass making has been in constant development for almost 4000 years to the present day. Glass was formed into vessels to contain precious scented oils and other liquid treasures. Glass as a chemically inert material was found to be the perfect medium for such objects. Combined with its aesthetic quality, truly fascinating products were created (Fig. 1b). In the current world of mass production and efficiency, highly sophisticated machinery has replaced traditional glass blowers. Highly skilled technicians are able to adjust technological processes to suit individual project specifications.

a) b) c)

Fig. 1a) Obsidian weapon, b) Glacier by Brodie Neill c) Canterbury cathedral

From early times, glass was considered a luxury item and was consumed by only the upper classes of society. With the invention of the float line and increased demand however, glass is viewed as an ordinary material today. We are in contact with glass almost everywhere - from our mobile phones, to the vessels we drink from. Just as raw diamonds require extra work to reveal their quality, glass structures require particular attention to unlock its true beauty.

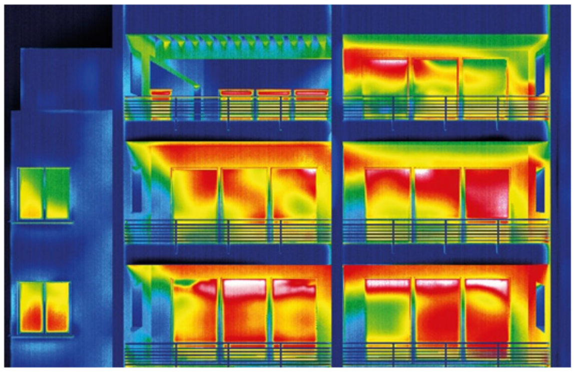
1.2. Design objectives

Glass as a transparent material allows architects to bring sunlight into our buildings (Fig. 1c). Similarly, it provides a connection between interior and exterior. The benefits of both these qualities to the human body and mind are unquestionable. Unfortunately, glass itself has poor inherent thermal insulation properties. As such, the use of glass in buildings is seemingly contradictory to our goal to reduce their energy consumption and limit the loss of heat through the building envelope (Fig. 2b). In recent years engineers and designers have refined envelope detailing to mitigate energy loss. Triple insulating glass units with gas-filled/vacuum cavities, framing elements incorporating thermal bridge details, an array of selective glass coatings, are available on the market. We are now investing in the development of methods to harvest solar and wind energy through the building envelope, (Bio PV cells, Active or adaptive solar shading systems, high-performance building façade, etc.) Energy passive buildings are our next goal. Glass structures will have to adapt to this trend.

A handful of parameters can be defined through the design process, however these often seem to contradict each other. Multi-parameter optimization methods could potentially be a tool to help designers with important decisions. The key to this mathematical approach is to define the optimum solution or at least an acceptable boundary interval. Importantly, buildings should be sustainable and demonstrate that all aspects of circular economy throughout the life of the building have been thoroughly considered. The question we face is what is the role of the structural or façade engineer in this process?

A potential strategy to address this goal is to move from the concept of primary structural elements and infill structures. Utilizing the building envelope so that the primary structure can benefit from extra stiffness, if not strength, appears to be a step in the right direction. It is indisputable that such interaction will introduce additional design challenges; special considerations when designing with a brittle material like glass will be required. Spontaneous failure will require to the study of failure modes and their consequences in early design stages.

a)



b)

Fig. 2a) cost and value interaction diagram, b) energy loss through glass / solid façade envelope thermal camera view

2. Design workflow and methodology

As engineers we are both challenged and inspired by an architectural concept. Our main goal is to develop the architectural concept into something which is safe and buildable, whilst not diverging too far from the initial aesthetic intent. It is often the expectation that the engineer delivers the initial 'reality check' on a project. In the current world climate where resources are scarce, value of structural glass application for the project shall be clearly defined and agreed between key stakeholders.

It is often very difficult to identify boundaries of acceptance for a particular project. The cost of a glass structure is often nonlinear; where relatively insignificant changes in design may increase the cost disproportionally (Fig. 2a). Considering the manufacturing processes, number of subcontractors able to carry out the work or increasing size and complexity may lead to a longer lead time or handling and installation difficulties. With more unknowns in the project, risk margins understandably increase. Critical for the success of every project beyond concept stage is to understand current manufacturing limitations, associated costs and procurement time. Early collaboration with industry is key to having a positive impact on the final product and cost.

Challenges in installation could be eased with reasonable achievable tolerances. Details must be capable of transferring load as well accommodating fabrication and installation tolerances. Dematerialization of glass connections is also a current but rather costly trend.

Discussions about anticipated structural movements and their implication on envelope design should be held at early stages of a project. The more challenging the glass structure, more detailed information will be required. However sometimes it is not sustainable or desirable to strengthen the primary structural system so a fine balance must be negotiated or additional techniques to accommodate deformations explored.

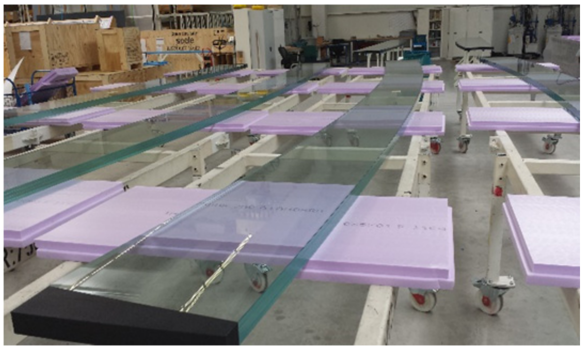
Replacement strategies, detailing of glass components as well as other associated cladding components and finishes must also be considered early on. The planned sequence of works may impact on the overall project schedule and this information is critical for the construction manager. If this coordination does not occur, there is a high risk of redesign or last minute fixes on site which may compromise initial design intent.

Envelope components have limited warranties with a wide range of design lives and maintenance plans. Accessibility of all components for inspection and potential replacement is key to a long lasting envelope.

The following design criteria are to be considered when designing with structural glass:

- Architecture, aesthetics, transparency
- Cost
- Compliance with building regulations
- Structural safety
- Robustness and redundancy
- Fire resistance
- Thermal performance and condensation
- Handling, production, installation & maintenance.

a)



b)

Fig. 3a) Installation of glass envelope TP Bennett, Arup, EOC, OAG, b) production of long span glass beams, Seele - Sedak

2.1. Engineering guidance

Towards the end of 1980's Peter Rice and Hugh Dutton in their book *Structural Glass* (Rice and Dutton, 1995) summarized ideas and projects concerning the structural use of glass which we still find inspiring 25 years on. Since then, many books, regulations and codes of practice emerged to give practicing engineers guidelines when designing with structural glass. Code committees are facing a difficult task not to the restrict use of glass however to set prescriptive rules to ensure public safety. Often engineers are asked to review or take part in this process to ensure that the code will be understood and is not contradictory to current design practice. Such work is helping engineers to understand the reasons behind those limitations and thus propose safe designs based on first principles when required. As such, with additional reasoning, innovative designs can be accepted by authorities. Performance-based codes will be the logical progression of such activities.

2.2. Structural challenges

Simplicity is usually the key to the success of a structure. Particularly in innovative structural glass projects it is always appreciated by contractors and building authorities if the structural load path can be clearly followed. Determinant structural systems are preferred. Glass structures are supported from substructures whose stiffness can vary from point to point significantly. Glass is a relatively rigid, elastic material and cannot redistribute load as easy as steel or concrete.

While all engineering calculations should be justifiable by first principles, structural glass projects are usually finite element analysis-heavy from very early design stages. Glass systems are completed with structural silicones, visco-elastic interlayers, nonlinear geometry etc. which is creating additional complexity in structural justification.

Perception of safety is clearly very subjective. Comparing the surface strength of a pane of glass as calculated according to various codes around the world, it is clear that the same glass design may be difficult to justify if relocated geographically. A comprehensive risk assessment should be undertaken for each individual design, instilling confidence in that design but also highlighting possible improvements or preventative actions. However, risk is not measurable only in terms of safety to the public; capital cost, disruption to businesses and reputation of business owing/commissioning such structures should all be considered equally.

In the use of structural glass we have traded ductility for redundancy. Standard procedure nowadays is the use of laminated glass. Stronger SentryGlas interlayers make it possible to bond glass sheets up to the thickness of an equivalent pane of fully monolithic glass. If the robustness of a structure is in question and disproportionate collapse is predicted, elimination of key elements and justification of projects scheme in a failure scenario is the next necessary step. Measures for mitigating risks beyond the building envelope itself are sometimes the cheapest and most effective solutions, for example to prevent failure due to car impact or explosives.

Possible redundancy mechanisms that could be taken into consideration following risk assessment:

- Layering of glass panes via lamination, interlayers and sacrificial ply's
- Alternative load paths, membrane catenary action or structural system modification
- Key elements
- Internal & external mitigation techniques

3. Integration

3.1. Hybrid structures

The concept of combining glass with other structural materials is not a new one. Iconic 19th century train stations and greenhouses (Fig. 4a) are examples of this, and technical marvels of their time. Nowadays, there is a constant flux of new projects where transparency is primary objective. A few recently constructed examples are shown in Fig. 4b, Fig. 5a. Both clients and architects, are pursuing this same objective for their own reasons. On the other hand, a similar push for smaller, more slender structural elements is creating challenges in terms of code compliance, where structural safety and structural performance are in question. Assuming that both trends will coincide eventually, the only solution will be to consider the contribution of the glass panels to the overall structural performance. This contribution can be significant, allowing for savings to be made on the amount of required materials and construction time. Current guidelines on the analysis, basis of design, design methodology, and constructability process are scattered and hence wider application of structures integrated with the envelope is still limited.

As engineers, we are more frequently facing requests from clients to design structures where envelopes consist of glass, which in the author's opinion, could significantly contribute to the total stiffness of the primary structure if designed appropriately. Cost vs. safety implications require careful consideration as it is expected that some capital costs could be redistributed due to the added project complexity and relative novelty of approach.

With limited knowledge in this field, it is important for engineers to drive the innovation and research in this growing area of the construction business, allowing for quick and effective answers to our clients' demands, while at the same time developing sustainable solutions.

a)

b)

Fig. 4a) Kew Gardens Palm House, D. Burton, R. Turner, b) Bombay sapphire distillery, Heatherwick Studio, Arup, Bellapart

Moving away from the concept of primary structural elements and infill structures could be beneficial. Utilizing envelopes structurally, especially for stability systems where this structure is on the “extreme fiber”, can bring benefits to the primary structure such as extra stiffness and potentially strength if feasible. It is indisputable that this interaction however brings additional design complexity. Especially with a brittle material like glass where spontaneous failure is possible and therefore requires to careful consideration of failure modes and consequences early in the design process.

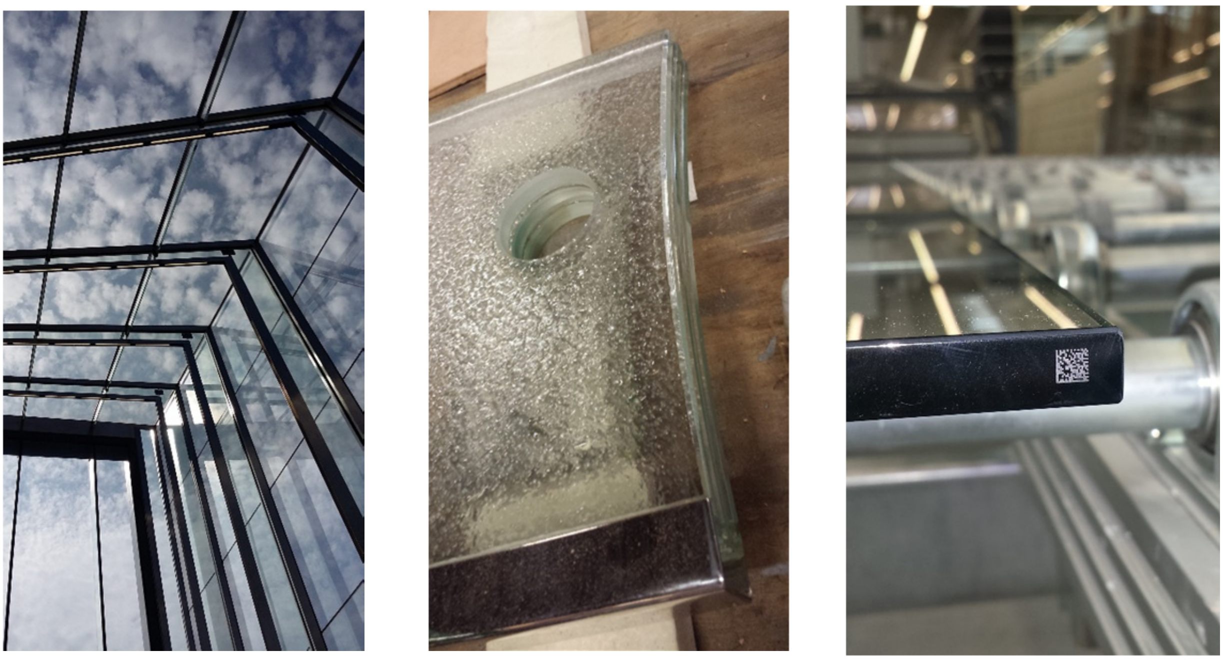
Small scale examples include glass edge protection caps, which are a typical mitigation technique to control damage and ensure longevity of the glass component. (Fig. 5b). However, stainless steel capping is considered very rarely in structural design, primarily due to concerns regarding the reliability of the adhesive.

3.2. New design techniques

The design process is full of parameters which often contradict each other. Multi-parameter optimization methods are currently being researched to help designers with their decisions, however the optimum goal is not yet clearly defined. Importantly, buildings should be sustainable where all aspects of circular economy throughout the life of a building is considered.

Parametric design has become a part of engineering and design. The consideration of changing forces has always been part of the design process. In the generative design method, the output is generated by a set of rules or algorithms. Generative methods have their roots deep in systems dynamics modelling and are by nature repetitive processes where the solution is developed during several iterations of design operations. Design optimization aims to reduce the time required to engineer a new design. Thanks to parametric modeling, design exploration techniques can follow a systematic, mathematical approach to acquire model behavior to the maximum extent. Design exploration is a powerful asset to the design optimization process. By minimizing, maximizing or zero-minimizing the design manually or automatically, numerical optimization techniques can help to improve the performance of the original configuration significantly.

BIM is well integrated within the construction industry; façade design will now have to keep up with this trend. An interesting initiative in this field is barcoding glass elements so that pre-defined information can be read during installation or even in the case of failure or replacement later in the life time of the project. (Fig. 5c)



a) b) c)

Fig. 5a) Tottenham court station, Stanton Williams, Expedition, Seele , b) Glass element with stainless steel edge c) Bar Code on glass, Seele

4. Conclusion

Glass is used deep in the sea, in space, and far beyond the Arctic Circle. The environmental conditions that glass in those applications are required to withstand are well beyond anything our structures are subjected to in typical building construction.

Thin and super-thin glass has been on the market for some time and possible applications for these are very slowly emerging. Thin glass has the potential to reduce the weight of our envelopes, for example. As such, geometrical stiffness can be exploited. Due to the thickness, only adhesive connection technology is possible in these applications. Even then, local eccentricities may cause significant bending stresses and should be avoided through symmetrical configurations. Together with glass coatings and interlayers, technology which can display information on glass may revolutionize envelope functionality as we know it.

With increased geometrical complexity of our envelopes we may well need some more advanced methods to adopt in design and construction. Parametric design, optimization and panelization in digital space are now being applied to more mainstream projects. Without such tools, the design process would be laborious and the level of refinement low. Additive manufacturing in construction was explored by the Massachusetts Institute of Technology, where examples of 3D printed glass have been reported. Due to the viscosity of glass at elevated temperatures, shape stability should be further investigated if such applications are to be employed in practical applications.

Acknowledgments

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