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Potential, challenges and guidelines for stretching the mass limits of structural cast glass

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Topologically optimized structural glass megaliths: Potential, challenges and guidelines for stretching the mass limits of structural cast glass.

F. Oikonomopoulou, A. M. Koniari, W. Damen, D. Koopman, I. M. Stefanaki, T. Bristogianni
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ABSTRACT: This paper introduces the use of structural topology optimization (TO) as a new design approach that enables the creation of monolithic load-bearing cast glass components of substantial dimensions with significantly reduced annealing times, rendering such components viable in terms of manufacturing. Using topology optimization, the glass mass can be optimized to match design loads whilst maintaining high stiffness and a homogeneous mass for even cooling. Initially, the two main TO approaches are discussed in terms of suitability for cast glass. A strain-based optimization is eventually preferred over Von Mises optimization in the specific study. To explore the potential of TO for optimizing structural cast glass components, three distinct studies are analyzed in ANSYS workbench: (i) a structural glass node, (ii) a cast glass floor and (iii) a pedestrian bridge. These lead to the establishment of a set of design/input criteria, taking into account glass as a material, casting as a manufacturing method, addressing also the safety of the structure. The design studies also reveal the inherent challenges of using TO for load-bearing glass components, which, in turn, lead to the establishment of design guidelines for developing a TO tool specifically for glass. Towards the real-life applicability of such complex-shaped, customized components, possible manufacturing methods are also discussed.

1 INTRODUCTION

Cast glass is a promising new structural material for architectural applications, particularly for the creation of all-transparent, robust, self-supporting envelopes (Oikonomopoulou, 2019). The shaping potential of cast glass is vast; it can virtually take any shape and size, allowing us to envision storey-high glass columns and entire monolithic envelopes. So far, this shaping potential has been little explored in the built environment, mainly due to the perplex and lengthy annealing process involved for glass components of substantial mass/thickness, which in turn renders their production unrealistic. As a result, structural cast glass components are typically applied in the form of solid blocks comparable in size to standard bricks.

Key factors that affect the annealing time are the thermal expansion coefficient of glass (characteristic of the glass composition), the amount of surfaces exposed to cooling and the thickness and overall mass of the object (Shand and Armistead, 1958). Essentially, the thinner the cross-section of the cast glass component, the exponentially less the annealing time[1].

[1] demonstrated also by the float production process: glass of 10 mm in thickness is annealed during its travel through the annealing lehr, from 600 ˚C to 60˚C, within approx. 20 min.

In this direction, an optimized cast glass geometry, following a high stiffness to weight ratio, can lead to a considerable reduction of the involved annealing time for its production.

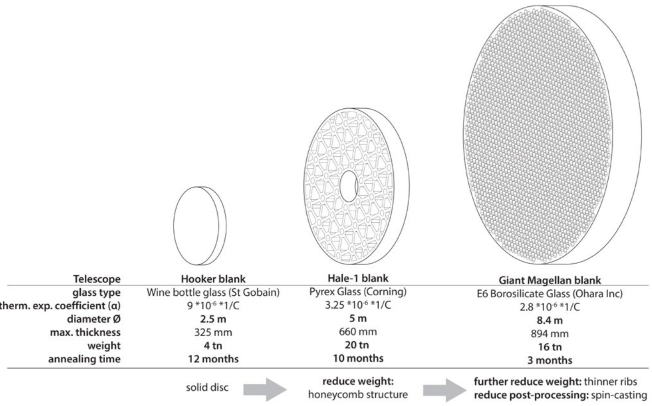

Figure 1: Evolution of the cast glass mirror blanks in size and annealing time due to smart geometry and improved manufacturing process

The design of the massive cast glass mirror blanks of the giant ground telescopes is the most characteristic example following this approach (Fig.1) : owing to its optimized honeycomb structure, each blank of the *Giant Magellan Telescope* required 3 months of annealing. In comparison, the solid mirror blank of the *Hooker Telescope*, 3 times smaller in diameter and thickness, required 12 months of annealing.

In this paper, structural topology optimization (TO) is investigated as a promising approach for designing monolithic, structural cast-glass elements of substantial mass in all three dimensions, with significantly reduced annealing times. Using TO the glass mass can be designed to match design loads whilst maintaining high stiffness and a homogeneous mass for even cooling (Oikonomopoulou, 2019). The possibility to generate cast glass forms of reduced mass and complex geometry, results in interesting structures of reduced material and most importantly, of the annealing time involved, rendering them viable in terms of manufacturing.

2 THE POTENTIAL OF TOPOLOGY OPTIMIZATION FOR GLASS CASTINGS

There are currently two main TO approaches: strain-based and Von Mises (stress-based) optimization. Common stress-based TO aims to minimise the stresses in an object for a given set of boundary conditions. Stress-based TO typically employ a Von Mises stress criteria, which is an abstraction that does not distinguish between tension and compression, allowing in turn for a simplified and faster optimisation progress.

Glass, however, is a brittle material, with a tensile strength at least an order of magnitude lower than its compressive strength. Essentially, if the von Mises stress criteria is applied to glass, the tensile strength becomes the main restrain, leaving underutilized the considerably higher compressive strength of glass. This will have to be evaluated in a later stage increasing, therefore, the amount of manual work needed. Research on stress-based TO for brittle materials has so far focused on concrete design, employing principle stress based-optimisation (Jewett and Carstensen, 2019) or dual material optimisation (Gaynor et al., 2013), which can distinguish between elements under tensile and compressive stress. However, these methods are still at an early stage, and due to their complexity have been limited to 2D case studies.

Strain- or compliance based TO is an alternative approach that aims to maximize stiffness of an object by setting as objective the minimization of the compliance energy of the structure. Compared to stress-based optimisation, it provides better efficiency in terms of stiffness as well as it uses the compressive capacity of glass more beneficially (Koopman, 2021). Though this should result in more reliable geometries, like stress-based analysis, it also does not distinguish between tensile- and compressive stresses. In addition, as stress is not directly taken into account, local peak stresses may occur. This is a risk for glass as it is unable to deform plastically to redistribute these local peaks. Thus, post-analysis is necessary in this case as well to check for possible peak stresses, increasing in this regard the manual work and time needed for each operation.

It is evident that none of the existing TO algorithms is fully fitting to glass. In this research, strain- or compliance based TO has been selected, as it is more suitable for a three-dimensional element and thus allows for a better exploration of the thickness reduction, which, in turn, has a major influence on the annealing behaviour of cast glass.

3 CASE STUDIES

To explore the potential of TO for optimizing structural cast glass components, 3 distinct studies are analyzed in ANSYS workbench: (i) a grid-shell node, (ii) a cast glass floor and (iii) a pedestrian bridge. These lead to the establishment of a set of input criteria, taking into account glass as a material, casting as a manufacturing method, addressing also the safety of the structure.

In all the projects, the glass composition selected is borosilicate glass since, although it is more expensive and requires higher forming temperatures, its low thermal expansion coefficient (compared to soda-lime glass) contributes to a considerable shorter annealing time and, therefore, allows for faster production. Additionally, it has similar mechanical properties and more stable thermal behavior.

3.1 *Structural glass node*

The first project which is going to be discussed refers to the design of a node for a free form, compression-based grid shell structure (Damen, 2019). The design of the shell is defined using form-finding techniques and TO is used for the node design.

The algorithmic methodology selected is SIMP (Solid Isotropic Material with Penalization method) and it is implemented through ANSYS Workbench. The problem formulation is compliance-based and additional constraints are applied referring to the proportion of mass reduction, as well as the element size of each node part. Regarding the latter one, firstly, a minimum thickness constraint is set, so that all the parts are sufficiently thick in order to be able to cast reliably. Additionally, the max. cross section size is defined since it largely affects the annealing time needed for the overall casting and, at the same time, assures that there is homogeneous distribution of the mass in the component. This will prevent from uneven shrinkage that could lead to high internal stresses in the component and ultimately failure.

After each TO iteration, the shape is post processed in order to create a smooth geometry and remove any sharp edges, in order to prevent the local increase of residual stresses during annealing. Afterwards, the geometry is applied for structural verification in the same software, in order to reassure that the stress values are inside the allowable limits.

The resulting shape is validated through prototyping and it successfully demonstrates the potential for designing glass structures that have a considerably reduced annealing time via using TO techniques.

Nevertheless, one of the main challenges of the project lies on the fact that, due to the small size and light-weight of the structure, it is highly susceptible to the varying wind loads; one dominant load case is hard to be defined. This is largely reflected on the TO process, since the variable wind loads change drastically the resulting outcome, rendering difficult to have one shape that could sufficiently serve diverging load scenarios. Thus, it is essential to have a governing load case that remains unchanged and ensures the necessary stiffness for the structure (e.g. self-weight), while the varying load cases (e.g. wind) should have a comparatively small influence.

In this regard, it can be claimed that either the main load case should be enlarged (e.g. by having an overall heavier structure) or the shell should be designed in a way that protects from direct climate effects so that the values of the variable load cases remain overall small. By following these principles, the result (Fig.2) is proven structurally efficient for different load cases and achieves sufficient material reduction, resulting in approx. 47% reduction in weight compared to the initial node.

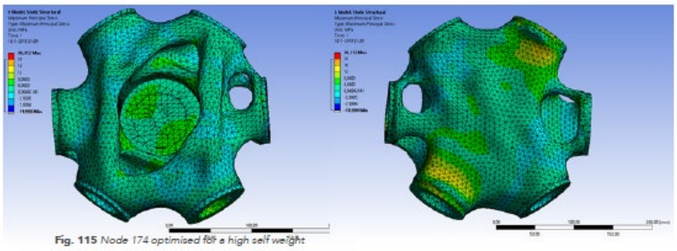

Fig.2: Optimized node design with increased self-weight as the governing load case.

Alternatively, the resulting form can derive from merging the outcomes of different load case optimization iterations in one final shape which, in this regard, has better redundancy and flexibility. The mass reduction is greater in this approach, yielding a 69% weight reduction compared to the initial node (Fig.3, left).

80 mm thick	max. 40 mm thick	max. 30 mm thick
8.7 kg	5.1 kg	2.7 kg
>48 hrs annealing	~ 16 hrs annealing	~ 4 hrs annealing

Fig.3: From left to right: Initial un-optimized node; node optimized with increased self-weight as governing load case; node design through manual merging of optimized designs for different load cases. Annealing hrs estimated based on the annealing of the bricks in the Crystal Houses façade.

An empirical estimation of the annealing times of the optimized nodes, based on a comparison with the mass/thickness and recorded annealing times of the bricks of the Crystal Houses (Oikonomopoulou et al., 2017) suggests great reductions of the annealing time of the TO cast components compared to the non-optimized node (Fig.3).

3.2 *Glass floor*

The next project refers to the design of a larger monolithic component; a topologically optimized cast glass floor which is aimed to be placed above an archaeological space (Stefanaki, 2020). In this case, an additional challenge is raised since, besides compression, a horizontal element has increased tensile stresses which, in the case of glass, are the most critical aspect for failure. The project was implemented with SIMP methodology in ANSYS Workbench.

The initial floor shape is defined as planar on top, so that people can walk, and as shallow vaulted at the bottom so that the relief of tensile stresses is facilitated. In terms of safety, one layer of float glass is added on the top side of the slab. It serves to protect the large monolithic piece from contact stresses which have been generally proved to be more critical than far-field stresses, activating different defects and deformation mechanisms and leading ultimately to failure (Bristogianni et al., 2021).

Similarly to the previous project, the problem is formulated as compliance-based and constraints are applied referring to the mass reduction, the element size and, additionally, the deformation, which is very critical in this case (Fig.4). In terms of structural performance, given that the available software can only apply one stress constraint in the optimization process, tensile stress was selected as the most critical for glass structures. The horizontal orientation of the slab implied a design value significantly smaller than the characteristic float glass tensile strength value and is calculated according to DIN18008 (German Structural Design Guidelines for Glass Constructions).

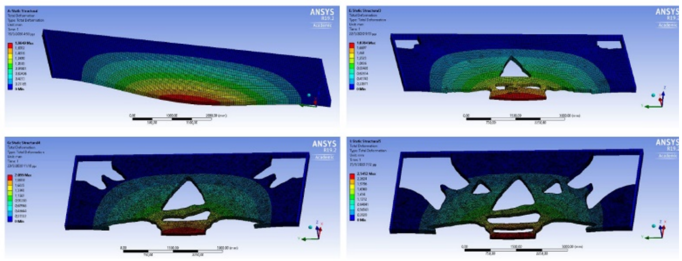

Fig. 4: Structural verification of the optimized design

Several other criteria are checked in a post-processing phase due to the fact that it is not possible to directly apply them in the optimization software. Firstly, the compressive stress is evaluated in order to check for peaks that exceed the allowable limits and, secondly, any sharp edges that may increase locally the residual stresses are removed. Moreover, given that this time a larger monolithic component is designed, transportation limitations are taken into consideration, as well as manufacturing criteria. These refer to the maximum size of sand mould that can currently be 3d printed and the minimum mould thickness that can sufficiently resist the hydrostatic pressure upon pouring the glass melt.

Additional limitations derive from the placement of the sacrificial layer. Particularly, the size of the holes in the slab design should not exceed a maximum value which ensures that the deformation on the float glass sheet and the subsequent tensile stress do not exceed the allowable limits.

A major drawback that renders the process time-consuming was that a lot of manual work was needed after each optimization iteration for post-processing the coarse mesh in order to apply it for the evaluation of peak stresses and check for the rest of the aforementioned constraints.

Despite the inherent limitations, the final result (Fig.5) proved that a solid monolithic structure with reduced mass (44,8% of the initial volume) could be achieved, introducing a new architectural language for the structural components.

Fig. 5: The final mass-optimized cast glass slab

3.3 *Pedestrian glass bridge*

The third project is related to the design of a monolithic pedestrian cast glass bridge (Koopman, 2021). Firstly, the general shape of the bridge is defined in the 2-dimensional longitudinal section and it is used as the initial point for the 3-dimensional TO operation. Similarly to before, safety is ensured through applying float glass layers on top of the cast elements. However, it is highlighted that this may lead in peak stresses due to unevenness in the glass surfaces and applying a silicone intermediate layer is suggested. Moreover, the monolithic structure is analyzed into separate large parts to meet the transportation limitations and also achieve the necessary flexibility and redundancy. Polyurethane is proposed to be placed in the intermediary layers between the cast elements.

Regarding TO, the most significant difference in this project is that Level Set Method is used instead of SIMP while working on ANSYS Workbench. This decision is based on the fact that clearer boundaries and smoother contours can be extracted with Level Set approach, since it uses the discrete iso-contours of a Level Set function for the optimization (van Dijk et al., 2013). Therefore, the amount of manual work needed for post-processing is considerably reduced in comparison to SIMP, where the final shape derives as a distribution of pseudo-densities (Bendsøe and Sigmund, 2003) and, thus, needs more work in order to be interpreted in a clear outline.

The initial setup is similar to the previous projects, but a tetrahedral mesh is used because of the Level Set approach. The problem formulation is compliance-based and constraints are applied related to mass reduction (maintaining ~ 30-35% of the initial volume), tensile stress and maximum member size; but min. size constraint is not available with Level Set. Since it is not possible to evaluate both the principal stresses during the optimization, a second step related to the structural validation for peak stresses has to be incorporated (Fig.6).

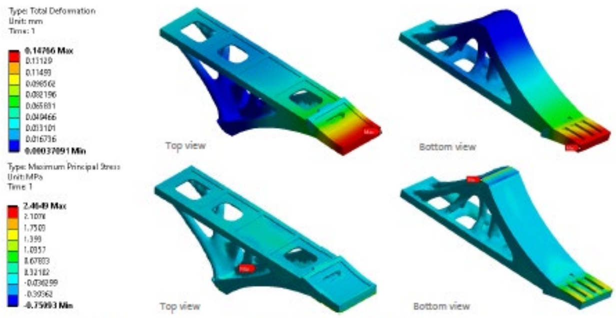

Fig.6: Plots showing the max. deformation and principal stress at the pedestrian cast glass bridge.

It needs to be underlined that two approaches are followed for the structural evaluation of stresses and deformation in order to better simulate the behavior of the structure (Fig.7); a linear, referring only to the float glass elements, and a non-linear analysis, including also the intermediary polyurethane layers. The non-linear analysis is mentioned to give better results than the linear one.

The final shape is defined after post-processing of the optimized outcome to remove any sharp edges that could cause failure during annealing.

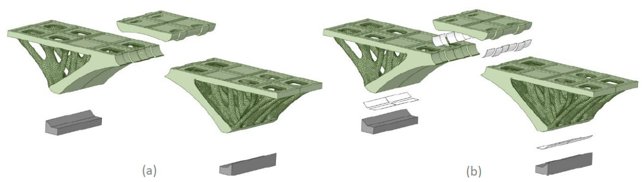

Fig.7: Model used for linear (only float glass) and non-linear (float glass and polyurethane layer).

4 MANUFACTURING

For customized components, such as the ones discussed in this paper, disposable moulds are preferred

over permanent, steel moulds, as they are significantly cheaper; complex shapes are generally difficult and expensive to produce in metal moulds, requiring bespoke CNC production techniques (Oikonomopoulou et al., 2018).
Thus, in order to make a cost-efficient production, a 3D-printed wax model of the geometry (Fig.8, middle) could be used as the positive for a silica-plaster investment mould, employing the lost-wax technique (Fig.8, right). Yet, conventional disposable moulds display inherent drawbacks. i.e. requiring intensive labour, post-processing and compromised precision of the glass object.

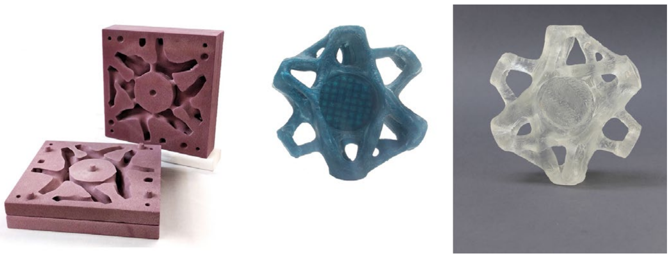

Fig.8: Left: 3D-printed sand moulds produced by ExOne; middle: 3D-printed wax positive model. right: cast glass prototype of the grid-shell node made by the wax model and a silica-plaster mould

A mould-free alternative, is to directly employ glass 3D-printing. Such a technology has been developed by MIT Media Lab (Klein, 2015). However, glass 3d-printing remains at experimental stage and faces several important drawbacks, such as lack of certification (due to the inhomogeneity of the printed material), size limitations and relatively high-costs.

The most promising manufacturing method is the use of 3D-printed sand moulds as described in (Oikonomopoulou et al., 2020). Such moulds exhibit low cost, quick production, scalability and high size accuracy (up to ± 0.1 mm). Initial kiln-casting experiments conducted at TU Delft using 3D-printed sand mould samples using different binders and surface treatments, discussed in (Oikonomopoulou et al., 2020) have shown the potential of this technology, pointing towards the direction of inorganic binders as the most promising, and confirming the high dimensional precision of the cast object (Fig.8, left).

Crucial for the industrial application of 3D-printed sand moulds for glass casting, remains the investigation and identification of a coating that allows for a completely smooth and transparent surface quality.

5 CONCLUSIONS

Overall, the discussed case-studies demonstrate the potential of using TO for engineering massive load-bearing cast glass components, opening a vast range of potential applications in the built environment.

In all three case-studies, a minimum compliance objective is followed; this is particularly meaningful for examples (ii) and (iii) where deformation is anticipated to be more critical than stresses. This decision is strongly related to the fact that it is not possible to apply different constraints for tension and compression during the optimization process. In this regard, compliance-based optimization is selected since it uses the compressive capacity of glass more beneficially. The stress constraint in this case refers to the allowable limit of tensile strength which, in the case of glass, is more critical. However, a major drawback in the process is that heavy approximations have to be done and it is necessary to manually evaluate the peak stresses after every TO iteration. This increases considerably the amount of manual work that has to be done and renders the whole process very time consuming. Therefore, the need for one tool customized to the brittle behaviour of glass and the significantly differentiated values of tensile and compressive strength is highlighted in all the projects.

Regarding the TO software, all the projects make use of gradient-based algorithmic methodologies. Particularly (i) and (ii) use SIMP, which is the most widely popular method, but case study (iii) follows the Level-Set Method aiming to have a clearer final shape that will need less post-processing.

Safety is also taken into consideration in all the case studies, either in the form of redundancy (e.g. by splitting the larger monolithic structures into different parts) and/or by placing float glass layers on the top in order to protect the monolithic elements from accidental impact (case studies ii and iii). Lastly, the need for having a fixed governing load case that will always provide the necessary stiffness is highlighted in order to ensure that the shape is flexible and the varying loads, e.g. wind, will have little influence on the resulting TO structure.

Kiln casting with 3d-printed sand moulds has been underlined as the most promising approach for the manufacturing of these components; whereas 3d printing glass may also be an option in the future.

Despite the inherent limitations, all case-studies result in well-established results taking into consideration the respective annealing, manufacturing and transportation criteria in the process and validating with small prototypes when possible. The final outcomes showcase the feasibility of creating these complex glass forms and the large potential of this new architectural vocabulary for the built environment.

6 DISCUSSION

Although the projects demonstrate successfully the large potential of this approach, they highlight at the same time the need for a tool customized to the brittle behaviour of glass and, most importantly, to the differentiation between the allowable limits regarding tension and compression. If this is achieved, it is expected to reduce drastically the amount of manual work needed for the post-processing and, thus, make the overall process less time-consuming.

Regarding the TO methodologies, although Level-Set method generally results in a clearer form, its strong dependence on the initial guess design is questioning its ability to result in a global optimum solution. In contrary, SIMP is well-proven to have good convergence and end in robust solutions. Therefore, it is believed that, despite the need for translation of the final pseudo density result, it should be selected for the algorithm implementation. Structural evaluation of principal stresses and deformation can be held through its combination with FEM equations. Regarding the mesh discretization, hexahedral elements can potentially be more useful for the application.

In this regard, since the evaluation of the structural criteria will be ensured (distinct tension and compression values will be set as limits in the algorithm), minimization of volume can be set as the objective, since it is the most crucial aspect for the reduction of the annealing time and thus, the viable production of the component.

The rest of the manufacturing criteria, such as the cross section size, can be applied with the adaptation of methods that have already been introduced, such as the maximum length scale constraint (Guest, 2009). Given that the annealing rate of glass can be described as a function of the size of the cross section (Shand and Armistead, 1958), it is evident that the value for the maximum element size constraint can combine both the limit for the range of allowable cross sections, in terms of homogeneous mass distribution, and the maximum allowable annealing time so that the result is time- and cost-efficient. However, other constraints, such as eliminating the sharp edges should still be done in a post-processing phase.

Regarding the design's voids, apart from checking their minimum and maximum size, it is important to assure that there is connectivity between them so that the mould can be removed in the end of the fabrication. This can be evaluated through applying the Virtual Temperature Method; converting the connectivity problem to a temperature problem and performing a heat flow analysis (Liu et al., 2015).

It is evident that research in the direction of integrating these criteria into an algorithm will be able to facilitate considerably the overall process and reduce the time needed. At the same time, this tool could be used for other brittle materials except for glass, such as unreinforced concrete, following experiments that have already been undergone in this direction.

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