Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Eva Schoenmaker
Student number	4693906

Studio		
Name / Theme	Glass design & transparent structures	
Main mentor	Dr. Charalampos Andriotis	Computational structural Optimization
Second mentor	Dr. Faidra Oikonomopoulou	Structural Cast glass
Argumentation of choice of the studio	While glass design is in many ways very novel, the studio integrates its innovative character with sustainability in terms of material use, coast and energy efficiency. The integration of this innovative aspect with efficient structures is what drew me to choose this direction.	

Graduation project	
Title of the graduation project	Adding a New Dimension to Glass Giants.
Goal	
Location:	The case study is either a glass floor in the Acropolis Museum in Athens or a pedestrian bridge in the Great Court of the British Museum.
The posed problem,	Structural cast glass offers a high shaping potential, strength and transparency. However, cast elements have been used in just a few load-bearing applications. The components that have been realized were constraint to a limited size. This is due to the long annealing process required for larger elements. Previous theses have researched the potential of creating massive structural cast glass components using Topology Optimization (TO). Topology optimization is a method to reduce the volume and thus mass of structural elements while keeping the stiffness. When applied for glass elements this can greatly reduce the mass and the annealing time of elements. Increasing the possibility of creating glass giants. However, in the optimization process this research has been limited to commercial software. In all these theses it is pointed out how they were constrained by the software. The TO algorithms in commercial software are oriented towards ductile materials like metals, that have a similar stress constraint in tension and compression. Glass however has a large difference in tensile and

	compressive stress. As a result, the optimized geometries following out of these software leaves the compressive strength of glass underutilized. Next to that, a post optimization step is required to evaluate the compressive values in the structure. A thesis done last year resulted in a new TO algorithm that is specifically made for glass. It includes formulas for the specific properties of glass, eliminating the need for extra steps. This algorithm can optimize 2D structures which can then be extruded to result in a 3D geometry. However, further minimization of the mass and thus annealing time can be achieved by an algorithm that can directly optimize in three dimensions. This thesis intends to contribute to the existing research by creating a tool for the design of 3D optimized cast glass components, which can take into consideration the specific structural properties of glass as well as manufacturing, annealing and specific design criteria.
research questions and	This thesis aims to create a new algorithm for the design a 3D topologically optimized glass structure. To achieve the purpose of this thesis, this study addresses the following research question: - What are the main aspects and limitations of a three-dimensional topology optimization for the design of massive cast glass structures? To answer this question several sub questions are derived: - What are the main/ principles limitations of the existing Topology Optimization software/tools? - What are the main topology optimization methods and what are their advantages and limitations? - How do different objective functions influence the outcome of a topology optimization? - What are the structural and manufacturing constraints for cast glass, where do they differ for 2D and 3D optimization? - What are the design constraints posed by the chosen case study? - What are the main benefits and limitations of the developed 3D algorithm compared to excising 2D algorithms for cast glass components?
design assignment in which these result.	The assignment of this thesis will be the design of a topology optimized cast glass slab, either for a floor or for a bridge. The result will consist of two parts. Firstly, the design of an algorithm. This algorithm will then be used for the design of the cast glass slab. The second part will be how the design can be manufactured as well as the connection details and assembly sequence.

[This should be formulated in such a way that the graduation project can answer these questions.
The definition of the problem has to be significant to a clearly defined area of research and design.]

Process

Method description

To answer the research questions and main objectives of this thesis, a combination of different methods is applied. There are three main phases that this research follows: exploration, development and evaluation.

The first step of the research is the exploration of the topic by gathering and analyzing relevant literature. This exploration results in the literature review, which encompasses the scientific studies and the theses which have been done regarding similar topics. The two main topics of this review are structural glass and structural optimization methods. A third part of the literature review is the discussion of the different case studies and their respective characteristics.

The information collected on the properties of glass and the process of casting glass will be used for defining the structural, manufacturing and annealing criteria. The review of structural optimization methods will be used to define the combination of type, solver and objective that will be applied in the algorithm. The analysis of the different cases studies will be used in defining any design constrains that follow out of the location and use of the structure.

The next step will focus on the algorithm development. This phase will start with the formulation of the optimization problem and the translation of the objectives and constraints following from the literature research into an algorithm. As it is expected that the algorithm will take a lot of computational time, testing will first be done on smaller domains. If the code proves to function as expected, it will be applied to the design domain as given by the case study. After which both the problem formulation and the algorithm will be updated as required, until a desired outcome is reached.

When a final geometry is determined, the connection details, construction and assembly sequence of the design will be worked out. Lastly, an evaluation of the design in comparison to previous projects (derived with commercial software and the 2D algorithm) will be done, to conclude on the performance of the new algorithm.

Literature and general practical preference

The review on the applications and limitations of structural glass will be mainly derived form the studies of Oikonomopoulou (2019) and Bristogianni et al. (2020) on this topic. The theses done on the topic of structural cast glass will also be consulted (Bhatia, 2019; Damen, 2019; Koniari, 2022; Stefanaki, 2020).

For the structural optimization the basis comes from the Finite Element method for which (2002) is mainly consulted.

For the basis of topology optimization Bendsøe & Sigmund (2003) is consulted. This book gives the fundamentals of topology optimization as well as an introduction to the SIMP method.
For the other topology optimization methods, the papers first introducing these methods will be consulted (Allaire, 2005; Xie & Steven, 1993; Young et al., 1999).
Furthermore, papers reviewing and comparing the different methods will be consulted (Sigmund & Maute, 2013; Yago et al., 2022).

Lastly, both the work of Koniari (2022) and Jewett and Carstensen (2019) will be considered when defining the constraints of the topology optimization problem.

A detailed list of all references can be found in the Bibliography of the p2 report. The following sources are the one cited above.

Allaire, G. (2005). Topology Optimization with the Homogenization and the Level-Set Methods. In P. P. Castañeda, J. J. Telega, & B. Gambin (Eds.), *Nonlinear Homogenization and its Applications to Composites, Polycrystals and Smart Materials* (pp. 1–13). Springer Netherlands.

Bendsøe, M. P., & Sigmund, O. (2003). *Topology Optimization. Theory, Methods, and Applications*. Springer Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-05086-6

Bhatia, I. S. (2019). *Shaping Transparent Sand in Sand. Fabricating topologically optimized cast glass column using sand moulds* [Master Thesis]. Technical University Delft.

Bristogianni, T., Oikonomopoulou, F., Yu, R., Veer, F. A., & Nijsse, R. (2020). Investigating the flexural strength of recycled cast glass. *Glass Structures & Engineering*, *5*(3), 445–487. https://doi.org/10.1007/s40940-020-00138-2

Chandrupatla, T., & Belegundu, A. (2002). *Introduction to Finite Elements in Engineering* (3rd ed.). Prentice Hall Inc. https://doi.org/10.1017/9781108882293

Damen, W. (2019). *Topologically Optimised Cast Glass Grid Shell Nodes. Exploring Topology Optimization as a design tool for Structural Cast Glass elements with reduced annealing time.* [Master Thesis]. Technical University Delft.

Jewett, J. L., & Carstensen, J. V. (2019). Topology-optimized design, construction and experimental evaluation of concrete beams. *Automation in Construction*, *102*, 59–67. https://doi.org/10.1016/j.autcon.2019.02.001

Koniari, A. M. (2022). *Just Glass. Development of a Topology Optimization ALgorithm for a Mass-Optimized Cast Glass Component* [Master Thesis]. Technical University Delft.

Oikonomopoulou, F. (2019). *Unveiling the third dimension of glass. Solid cast glass components and assemblies for structural applications.* [PHD dissertation]. Technical University Delft.

Sigmund, O., & Maute, K. (2013). Topology optimization approaches. *Structural and Multidisciplinary Optimization*, *48*(6), 1031–1055. https://doi.org/10.1007/s00158-013-0978-6

Stefanaki, M. I. (2020). *Glass Giants. Mass-optimized massive cast galss slab* [Master Thesis]. Technical University Delft.

Xie, Y. M., & Steven, G. P. (1993). A simple evolutionary procedure for structural optimization. *Computers & Structures*, *49*(5), 885–896. https://doi.org/10.1016/0045-7949(93)90035-C

Yago, D., Cante, J., Lloberas-Valls, O., & Oliver, J. (2022). Topology Optimization Methods for 3D Structural Problems: A Comparative Study. *Archives of Computational Methods in Engineering*, *29*(3), 1525–1567. https://doi.org/10.1007/s11831-021-09626-2

Young, V., Querin, O. M., Steven, G. P., & Xie, Y. M. (1999). 3D and multiple load case bi-directional evolutionary structural optimization (BESO). *Structural Optimization*, *18*(2), 183–192. https://doi.org/10.1007/BF01195993

Reflection

What is the relevance of your graduation work in the larger social, professional and scientific framework?

The project aims to add to the research regarding the structural application of glass. While the structural use of glass is still very novel, the combination of the high compressive strength, durability and recyclability give it the possibility to compete with common construction materials like concrete and steel. However, for this to be possible it is needed to bring down the production cost and annealing time. The ability to create structural elements that are optimized for volume as well as manufacturing and structural constraints, will make the production of glass giants more feasible.

Anna Maria Konairi showed that it is possible to overcome the limitations set by commercial software in the design of TO cast glass elements. However, the new algorithm limits the design to a two-dimensional domain. There is still potential to further optimize structures in all three dimensions. This will not only further minimize material use and annealing but consequently give way to a new architectural language for glass structures.

Furthermore, with the growth of the population and the ageing of the existing infrastructure there is a higher and higher demand on the building industry. As the building industry is one of the largest emitters of CO_2 it becomes increasingly important to make efficient use of resources and include recyclability in the designs.

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