

Reflection

Glass is a brittle, but also strong material depending on how it is designed. The application of glass is different per industry, but for the built environment it is mostly used as skin of a building or as separation wall. Till now, it is not yet used as constructive component in a building. Currently, the focus of constructive glass research was mainly on wall structures, but minimum in span structures. The topic of this thesis concerns reconstruction historical of vaults with cast glass and showing the potential of cast glass next to the traditional materials. This way, original vault can be brought back thanks to the complex geometry possibilities of cast glass and the use of glass at its strongest.

The reflection contains two topics: 1. The graduation process and 2. The societal impact of the research.

Graduation process

The graduation studio is about sustainable design. Glass which is currently used in the built environment can only be downcycled. This is due to the added materials to the glass surface which makes it less easy to recycle glass as material for the same purpose. By using cast glass and dry connections, the quality of glass remains and can be recycled in full potential. This way, minimum new raw materials are required for re-using the glass which suits the circular economy.

The approach of literature research was based on 'starting general and zoom into the detail slowly'. This way, the research started from heritage. Here, the definition of reconstruction is stated, the debate regarding restoration and reconstruction is briefly discussed and the guidelines are stated. Based on this, glass and traditional materials for heritage application are discussed. To conclude, all gathered information is used to understand the case study, The Notre Dame de Paris, and how to approach the use of cast glass as part of the reconstruction of the building after the fire in April 2019. The value components of the Notre Dame de Paris' vault are summed and included in the design criteria. After the brief approach of heritage, the vault structure principles are discussed. The forces, masonry vaults and traditional construction methods are discussed. This way, the design aspects of vaults are summed which are part of the design criteria. From this point, the literature research zooms in into the topic structural glass and where cast glass is used in practice. Again, from this study, the most important elements are used for the design criteria. To be sure I did not miss major elements regarding structural glass research, I used the PHD book of Faidra Oikonomopoulou as reference. Before starting the design process in the graduation process, all design criteria are summed in one chapter with original and first approach dimensions of the vault.

Personally, I think this approach worked out well. As this literature is step by step zooming into the details. I like to work pragmatic and not include information that has minimum impact on the design process. The downside of this approach is that I am excluding information that might be useful later in the design process. Of course, during the design process, small literature checks were performed to understand more details. To conclude, my approach made sure I did not have to stress about the deadlines and still have all required information for the design process.

Research and design are in different ways related to each other. First, design criteria are based on the literature research. This was the starting point of the designing phase. In light of not over dimensioning of the new construction with glass as this is a waste of material and energy, simulations were performed. Thanks to the simulations and design criteria, dimensions were set for the vault and its structural arches. During this process, I had difficulties with the FEA Diana software as the results were not displayed or were incorrect due to setting issues. Also, the input models were incorrect in

the beginning. This part of the design process took me three weeks. If there has been software support from the university, this might have been shorter. In the end, I was able to solve the software problems with the help of another student who was facing the same issues. Once the analysis on the simulations were completed, I started the next step of the design phase: the components.

Designing the components of the structural arch was a challenge. Sketching the components on paper did not tackle all problems of tessellating the existing geometry of the vault and design criteria which are based on the literature research. Therefore, I made physical models which represent the interlocking and collaboration of the components in the structural arch. The variants were modelled in Rhino for a more precise component to understand the challenges. For now, this was done manually. My level of parametrical design is not advanced enough to create the components automatically. Also, my interest level is not in parametrical design, but in how to produce these elements. Therefore, all the manual work was time consuming, but this way I did understand what was and was not possible in creating moulds for the components. This part of the design process was mostly based on trial and error. The realization level of the moulds and its adjustable components was tested by actual building the moulds out of wood. This way, I found out some first sketches of the mould in 3D were not possible. Also, tolerances in dimensions must be considered. Only when I was building the moulds, I realized 100% precision work was not possible for now. Therefore, the relationship between research and design was based on a foundation of design criteria related from literature research and trial and error during the design process. The variants were discussed with the mentors to understand their thoughts and concerns. Only the most potential variants are included in the thesis.

The keystone was first designed as a full cast glass component. Many decisions were made during this design process. However, when the final option was reviewed, I realized it was a complex component. Also, the appearance of the component changes in comparison with the original keystone. Another limitation during this process was the simulation of the behavior of the keystone in Diana FEA. However, due to software limitations, it was not possible to visualize this. The choices which are made when designing the keystone are based on assumptions. In the end, this was not the best way to go, and the decision was made to go back to a limestone keystone. The original keystone was carved on location to fit in the arches. The new designed limestone is part of the arches as a part is integrated. Now, the arches do not conflict. This method reduces mechanical, physical, and designing challenges.

The first intention was to design a web out of cast glass components. However, I realized this would not be a simple and cheap option if this was realized. There were too many risks during the production and assembly phase. Also, multiple moulds would be required to create the curvature and connection with the arch. Therefore, other options were explored with float glass. In the end, this option was simple, and standardized for every possible situation for a vault. Every pattern can be engraved in the float glass, and thanks to the lamination process, the web will increase in safety. Therefore, it was a good choice to step back from a full cast glass vault and show other potentials to realize the same effect.

Finally, the interlayer and assembly processes were studied. Another student of the BT graduation group was focusing on interlayers for cast glass. Therefore, she shared her findings regarding this topic. Next to her findings, research was performed to understand future materials which can be used as interlayer for cast glass. This might be an option in the future, but when cast glass structures are designed. Based on my own criteria, I choose two different interlayers: soft aluminum and VIVAK. Depending on the position in the arch, the interlayer is applied. High compressive forces are mainly in the arches, so aluminum interlayer is applied there. The tessellation is made there where it is not visible from the ground floor 32m down. VIVAK is a transparent

interlayer and is used between the web and arch. This way, the interlay does not interfere with the optical experience of the vault, while different materials are used per component.

In the end, the lockdown due to Covid-19 did not make it easier when writing this thesis as quick questions to other students were not possible. Also, consults via Skype/ Zoom were challenging as making a quick sketch to share thoughts during the meeting was not done easily. All had to be prepared, even more than the consults in the studio. In the end, the mentors and I were flexible and took the time to understand each other.

Societal impact

The results of this thesis are meant to show the potential of cast glass for reconstructing heritage's roof structures. This way, a method is shown to design with a material that can be designed to full potential of its own properties and which can be fully recycled. For example, the case study of this thesis was the Notre Dame de Paris' vault. A vault is a compression-only structure. Glass has a high compressive strength and therefore it makes sense to show the potential of this material for architecture and not only for structural purposes. As glass can be fully recycled, it contributes to a circular economy.

Every heritage is restored or partially reconstructed through time. This way, the building is aging through time and layers of generations and knowledge is shown. By using cast glass, the latest technology of this time period is used. Using glass is not only giving the structure transparency. This is a choice as glass can also be made translucent or solid. It is about showing a historical framework which is blurred by using glass. Furthermore, this thesis does not only show the potential of cast glass for heritage, but it can also be applied for new architecture buildings. As the thesis shows the complexity of reconstructing a vault of a heritage, it is easier to apply the structure for a completely new building without restrictions from heritage conservators.

As mentioned before, the use of cast glass in the built environment is still new. Till now, most research is performed on vertical structures such as walls. This thesis shows the potential of cast glass in the built environment for roof structures.

On the one hand, glass requires a lot of energy till it can be casted, but when the energy is generated in a sustainable way, this should not be a problem for the environment. On the other hand, cast glass can be fully recycled, just like steel. This way it contributes to a circular and sustainable world. Using cast glass is currently expensive as it is not used regularly in the built environment. This is the case for any product in every sector. When a product is sold more often, the production process will become more efficient and cheaper. This way, the material and the cast process will become cheaper. The first float glass window was very expensive. Nowadays, nobody can imagine a building without window glass. It is all about supply and demand.

By introducing cast glass in the world of restoration and reconstruction heritage, a new discussion will start between the 'keep the original state' group and the 'adjust the building for the needs of today with the newest technology' group. A discussion is always good to understand the change and if it is applicable for every context, location, building and purpose. Cast glass will not be the solution for every building, but for some buildings it fits perfectly.