10 Recommendations

10.1 Introduction

Based on the main findings of this research, this chapter discusses the limitations of the applied research and provides recommendations for the further investigation of cast glass for structural members and systems.

10.2 Limitations of the research

Aim of this research was to manifest the potential and limitations of using cast glass for structural applications in architecture. This was achieved by developing two distinct structural systems for self-supporting envelopes made of cast glass components without the need of a secondary supportive structure. While these systems have been well received by the scientific, engineering and architectural communities, certain limitations of the presented work need to be discussed in order to define the validity of the systems in a wider sense and allow for their further applicability. These limitations are briefly discussed below; recommendations on their further development are given in section 10.3.

Firstly, the validation of both systems was experimentally conducted. As already mentioned, the described adhesively bonded glass block system has been developed in collaboration with, and support by, the industry. Accordingly, all experiments for this system used industrially manufactured glass blocks of high dimensional accuracy and surface quality. The provided results can be used as design guidelines for future applications. The second, interlocking system was developed within research context and had significantly less funding for the preparation of prototypes and the conduction of experiments. In this case, all prototypes were made by kiln-cast glass blocks at the *Glass & Transparency Lab* of TU Delft and were manually post-processed. These blocks presented considerably lower dimensional accuracy and surface quality compared to the ones produced by the industry. These aspects had a significant influence on the experimental results, providing compromised values compared to prototypes made by industrially produced blocks. Thus, in this case, the experiments provided a qualitative guideline on different variables that influence the system but should not be used as strength values. The revalidation of this system with high-accuracy industrially made blocks is necessary before its real application in the built environment.

Secondly, the in-depth numerical modelling of the presented systems remained out of the scope of this study but could further contribute in refining their mechanical behaviour and properties. This in turn can lead to reduced safety factors and hence, to more slender and elegant solutions. The use of more slender and lightweight cast glass blocks also decreases annealing time, reduces the need for raw materials and decreases manufacturing costs.

Thirdly, this dissertation focused on the structural behaviour of cast glass assemblies. The strength of individual cast glass elements and the effect of flaws on their strength was only briefly discussed. In this direction, a study on the strength of cast glass and the establishment of standardized strength data would greatly facilitate the widespread application of cast glass in constructions.

Moreover, the thermal performance of systems out of cast glass components has not been addressed in this thesis. In principle, the monolithic nature of cast glass results in a high U-value and relatively poor thermal insulation properties. This is perhaps the biggest drawback in using cast glass in architectural envelopes, especially nowadays, where energy-efficient buildings are becoming more and more essential. The development of integrated solutions for cast glass envelopes with improved thermal performance would make cast glass considerably more appealing to the engineering and architectural community.

In addition, economic aspects related to the potential cost of the developed systems could not be directly assessed, due to the lack of disclosed cost data in any of the few realized projects, including the *Crystal Houses* façade. The, so far, limited demand of cast glass applications has led to the absence of a standardized manufacturing process and hence, to increased manufacturing costs. A thorough study on the establishment and the cost-effectiveness of a standardized cast glass production for structural components is essential for spreading cast glass elements into the market.

Finally, although the shaping potential of cast glass was largely discussed throughout this dissertation, it was only explored through the development of interlocking glass units. The geometry of the blocks used at the adhesively bonded system, developed for the *Crystal Houses* façade, was already defined and could not be altered. The shaping potential of cast glass can be further explored and lead to cost- and structurally-effective solutions, if design criteria in respect to the casting method, such as the ones discussed in Chapter 7, are incorporated from the initial design stages.

10.3 Recommendations for further research

Cast glass components for structural applications are still at an early stage of development and have been little explored. This thesis showcases the structural potential of cast glass by focusing on the development of building systems for self-supporting envelopes. The following recommendations do not only refer to the further improvement of the developed glass systems but aim on providing a wide overview of the aspects of cast glass that can and should be explored in the future.

10.3.1 Recommendations on the adhesively bonded glass system

The innovative glass masonry system developed for the *Crystal Houses* façade illustrates the great potential of adhesively bonded cast glass bricks as an answer to the quest of structural transparency. The pioneering research conducted can be used to evolve variable designs for architectural projects where maximum transparency is desired. Different types of clear adhesive can be applied according to the specific structural demands and possibly allow for larger tolerances in the fabrication process of the bricks. The greatest engineering challenges and practical implications of this system are intervened with the nature of the adhesive involved and the irreversibility of the structure. Further research is strongly recommended towards finding a thicker, clear adhesive that can accommodate the dimensional tolerances of the individual components in its layer while ensuring the desired structural performance. A promising solution would be the development of a foil that allows for in-situ lamination of the components by controllable heating. Such an adhesive technology would facilitate the construction and guarantee the desired visual result as well. Towards circularity, research on finding an adhesive that can be eventually dissolved and preferably reused is highly recommended.

10.3.2 Recommendations on the interlocking cast glass system

Further research is necessary for applying the proposed interlocking cast glass system in reality. Contrary to the presented adhesively bonded system, due to time and financial limitations, the investigation of this novel cast glass system has been made utilizing kiln-cast glass blocks that were made using disposable moulds at the *Glass & Transparency Lab*. The produced components were of significantly reduced dimensional accuracy and had a low surface quality. In turn, these aspects had a significant influence on the overall performance of the tested specimens. In order to derive accurate strength data it is essential that the proposed interlocking system is re-investigated and re-validated using industrially produced components of high accuracy and fine surface quality.

The current research focused on existing, readily available, PU interlayers for the validation of the proposed interlocking cast glass system. The chosen interlayer served its purpose of proving the feasibility of the system but is by no means the optimum choice – its creep resistance needs to be further examined. It is therefore recommended to investigate in more detail the effect of different interlayer materials, of various thicknesses and under longer creep duration, on the structural performance of the assembly. A promising solution would be the engineering of a composite (sandwich) interlayer as proposed by (Frigo 2017) with softer external layers, which can adapt to surface imperfections and displacements occurring under axial load and an inner layer that would be stiffer and more resistant. The possibility of using soft aluminium as an interlayer could also be investigated.

Complementary to this study, further research should focus on the engineering of the necessary peripheral constraint structure, offering compression in the direction perpendicular to the shear key surface, and on evaluating the effect of different pre-stress rates in the stiffness of an interlocking assembly. Attention should be given to the interface between the peripheral structure and the interlocking assembly and to the effect of different values of pre-compression on the assembly. It is anticipated that the pre-compression of the assembly can largely increase its out-of-plane loadbearing capacity. In addition, a detailed study has to be contacted regarding the assembly mode of the system in order to ensure its proper alignment and installation prior and during the necessary pre-compressing. Finally, considering a circular approach, a holistic proposal for the buildability of the interlocking system should be made, including the sealing and the un-sealing of the system during its eventual disassembly.

10.3.3 Possible other applications

The conducted research proved the potential of using cast glass for self-supporting structures that can evade the 2-dimensionality of float glass and the inherent structural challenges of it. Yet, self-supporting envelopes is only one of the possible structural applications of cast glass. Both developed systems can be adapted to create compressive structural members such as full-glass columns, arches and domes. Cast glass columns are of particular interest, as they are a promising solution for transparent structural members, capable of transferring the compressive loads in a building while allowing for light and space continuity. Research on adhesively bonded and interlocking cast glass columns, by (Felekou 2016; Akerboom 2016), in their MSc graduation thesis supervised by the author of this dissertation, have yielded promising results.

Another attractive and fascinating new field of application, especially for the interlocking cast glass system is its application for the structural restoration of historic monuments. The author of this thesis has been co-awarded as co-initiator a *3TU.bouw 2016* grant to further develop this idea. The concept is to use cast glass elements to rebuild the missing parts of monuments, from masonry walls to columns and decorative elements, as shown in (Barou 2016). This is in principle possible with advancements in glass casting technology, allowing for a vast possibility of shapes to be produced in glass. Hence, a fully transparent addition can be realized providing an answer to the ongoing debate of the materialization of restoration schemes. A glass restoration can demonstrate the monument both in the original and damaged condition at the same time, will not detract from its traditional setting and the balance of its compositions, and will preserve its original aesthetic and historic value. Moreover, it can provide a structural reinforcement for the monument due to the mechanical properties of glass. The principles of this new concept can be found at (Barou et al. 2018).

10.3.4 Investigating the strength of cast glass

Cast glass is still in an infant stage of development regarding structural applications in the built environment. As discussed in Chapter 9, the strength of cast glass structural components is a relatively unexplored field – there are yet no guidelines nor standardized strength data for such elements. As a consequence of this, the existing applications rely either to extensive experimental validation or to a secondary substructure that ensures the structural integrity of the assembly. Hence, there is need for further research on the mechanical properties of cast glass and in particular on the influence of critical flaws. Particularly interesting is the investigation of the influence of the flaws occurring in the meso-structure of the solid glass, such as cord and inclusions to the total mechanical behaviour of the cast components. A consistent recording of the strength of cast glass components and a standardized production process can further reduce the material factors involved resulting to more slender and cost-effective cast glass solutions. For applications on the built-environment fire safety should as well be addressed and investigated. Proposals can include the glass type involved as well as the development of elegant, discreet safety mechanisms in case of fire.

10.3.5 Circular cast glass components out of glass waste

Glass casting is a promising manufacturing method for reintroducing discarded glass that is currently not recycled in the supply chain. Furthermore, by employing a dry-assembled, interlocking system such as the one discussed in Chapter 7 and Chapter 8, a fully reversible, circular building system can be achieved. The author of this dissertation has been co-awarded a *4TU.bouw 2017* grant and has been co-nominated for the *New Material Award 2018* for this idea and its first findings. Glasses of other recipes than soda-lime – such as mobile phone screens, crystal-ware, ovenware, laboratory-ware, light tubes, old TV screens, art glass- although pure and recyclable, end up as waste due to the lack of a recycling facility specialized in these glasses. Recycling them together with soda-lime is not possible by the industry as that would alter the end-recipe and also result in a different melting temperature. However, employing discarded glass of other recipes in cast components can be a way to reintroduce it to the supply chain. This alternative manufacturing method allows the use of customized recipes and their remelting without the aforementioned infrastructure implications. In that sense, everyday glass waste can be recycled into cast glass components. Through this initiative, *Pyrex*® trays and artware, even mobile phone and computer screens, are redirected from the landfill to the design and architecture sector, helping to tackle the scarcity of raw material resources. The first experiments at the *Glass & Transparency lab* of TU Delft with different glasses and cooling techniques have resulted in a wide range of clear, coloured, translucent and opaque/marbled circular glass elements. The first findings on the recycling by kiln-casting can be found at (Bristogianni et al. 2018b). In the future, extensive and systematic research is necessary for defining the mechanical properties of these new type of components.

10.3.6 Development of cost-effective fabrication methods

The real revolution in cast glass structures will come when a cost-effective production technique will be developed. The high costs that have restricted the application of cast glass components in just a few structural applications, are a result of the production time, mould-making and post-processing needed. The type of mould and glass used have also a great impact on the accuracy of the resulting component.

First of all, there is need for further research on the mould technology for cast glass elements. So far, the cost of high precision steel moulds has limited the number of different components to just a few in a structure. Research should focus on alternative mould fabrication technologies, such as adjustable steel moulds that can generate components of different sizes by the same mould. For customized or individually made components a promising solution is the development of 3D printed sand moulds, similar to the ones that have been recently used for metal casting. Research and experimental work by (Bhatia 2019) under the supervision of the author on the use of 3D-printed sand moulds for glass casting has already yielded promising results, suggesting the potential of this fabrication method for customized solid glass components.

Post-processing is a significant factor on the overall manufacturing costs and should be avoided; both manufacturing and construction of cast glass blocks for architectural envelopes require a high accuracy level. Spin-casting and press-moulds are two ways to achieve a higher precision.

The real breakthrough in cast glass structures would be the development of a low-expansion glass recipe with low working temperatures and production cost that would eliminate the size constraints and post-processing of soda-lime and borosilicate glass, allow for faster cooling and, in turn, for a faster and more economical production.

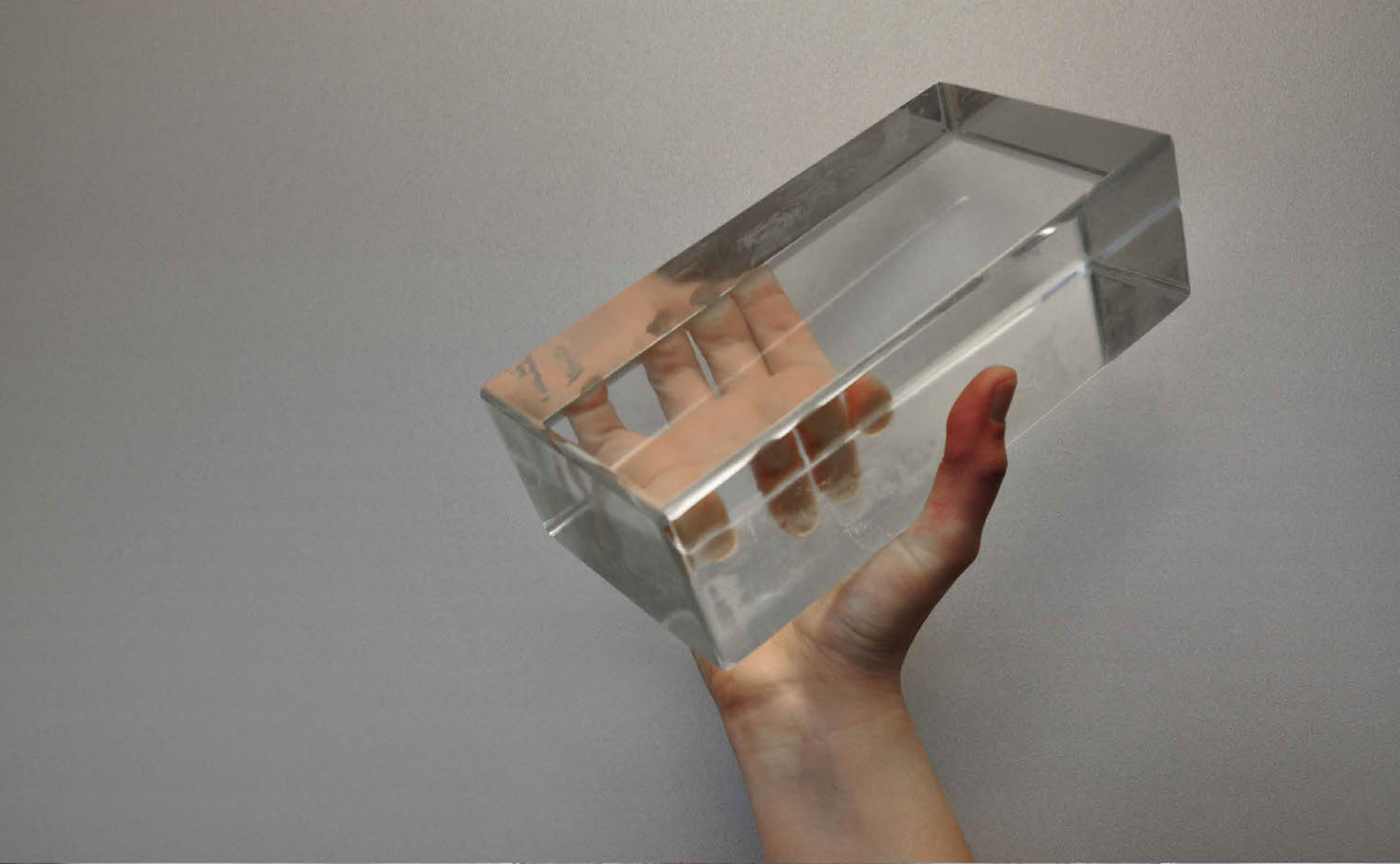
10.3.7 Optimizing the geometry of the components with respect to the properties of glass

So far, there has been little exploration on the shaping potential of cast glass. The structural cast glass components of the realized architectural projects mimic shapes derived from masonry structures – same as many of the marble decoration details in Greek temples are the descendants of the older wooden connections.

Yet, glass as a material has different properties and manufacturing process that in turn call for different forms. Osteomorphic blocks such as the ones presented in Chapter 7 and Chapter 8 are closer to this principle. Research on the optimization of the form of cast glass components can result in a more cost- and time-efficient production; i.e. honeycomb blocks can be lightweight yet stiff enough to create architectural structures similar to the ones realized. The glass mass can be optimized to match design loads whilst keeping the mass homogeneous for even cooling. A good example is the topologically optimized cast glass grid-shell node developed by (Damen 2019) for his MSc thesis under the supervision of the author of this dissertation. The resulting node is reduced by approx. 70% in mass compared to the original solid variant. Such reduction in mass is essential for reducing the requested annealing time which is currently one of the biggest drawbacks of cast glass components; a reduced annealing time can in turn, render cast glass components a financially competitive solution.

10.3.8 Improving the thermal performance of cast glass structures

The development of integrated systems that can improve the thermal performance of cast glass structures is highly encouraged. One of the biggest drawbacks of the current systems is the unsatisfactory thermal performance due to the monolithic nature of the glass and the absence of a cavity. Possible solutions to be investigated include the development of structural cast units with embedded cavities that do not compromise to a great extent the mechanical properties and transparency of the components. Components can be also developed to compensate for the energy loss; for example solid cast glass elements with an embedded lens system can be studied to concentrate and store solar power. It should be noted, however, that the high accuracy of the involved lenses and the perplexed geometry of the components may result in high manufacturing costs. An alternative approach is the study of integrated systems utilizing both cast glass elements and float glass for the creation of curtain walls and double-skin facades of improved thermal performance.



The two developed systems utilizing solid cast glass components.
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