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Cast glass arches, vaults and domes: case studies and design methodology

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Abstract

Cast glass is an excellent candidate for achieving fully transparent arch, vault and dome structures. By casting, voluminous, free-form glass components can be produced that fulfil the complex geometry requirements, offer increased compressive strength and maximize the incoming sunlight. Nonetheless, the application of cast glass in such structures is seldom seen; manufacturing challenges, uncertainties over the strength of the material, missing guidelines on the assembly methods of the components, lack of engineering norms, and the associated research and development costs to overcome those barriers, are some of the key discouraging factors. This paper explores several realised case studies of small-scale, cast glass arches, vaults and domes, where the TU Delft Glass Research group was involved in the R&D process, as well as unrealised case studies developed by the group (Fig. 1). The main challenges and developed solutions for each project are described, focusing on three main aspects: (i) the manufacturing challenges linked with achieving the desired curvature, (ii) the assembly method and mechanical validation of the system, and (iii) the construction ease of the system. Based on the comparative study of the selected projects, the paper aims to provide a design methodology for future projects employing cast glass curved structures.

Keywords: structural glass, cast glass components, cast glass shells and arches, glass casting and post-processing, adhesive bonding, interlocking components, adaptive moulds

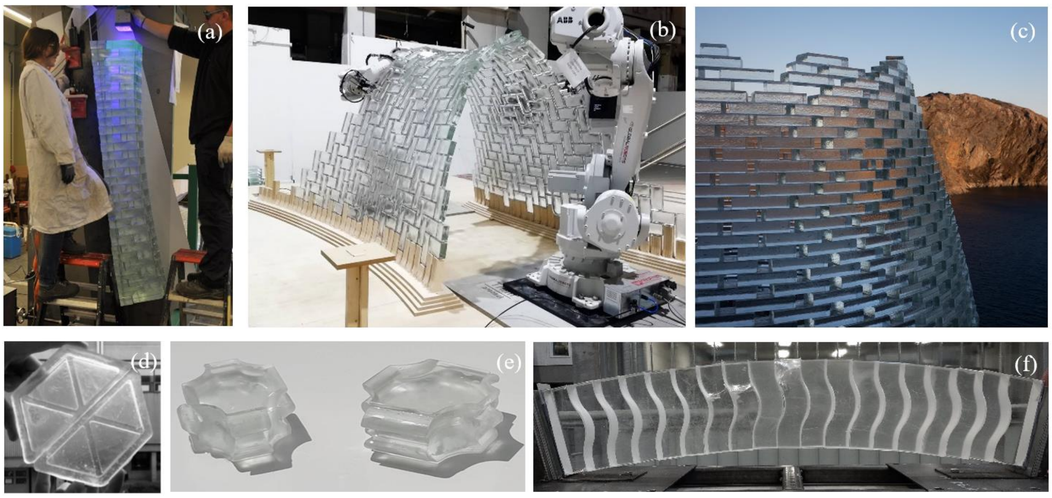


Figure 1. Cast glass case studies: (a) architrave assembly for the Crystal Houses Façade, Amsterdam (MVRDV), (b) robotically assembled LightVault, London (Princeton, SOM) (c) Qaammat pavilion in Greenland (Konstantin Arkitekter), (d) ribbed components for a geodesic dome (T. Bristogianni) (e) interlocking glass voussoirs cast with an adjustable mould (F. van der Weijst), (f) prototype for a cast glass interlocking bridge (A. Snijder).

1. Introduction

With the Industrial Revolution enabling the use of cast and wrought iron in building structures, large-span, glazed vault and dome structures were made possible, significantly increasing the incoming daylight in public buildings of the Victorian era (Fig. 2a, b). Ever since, transparent roofs fascinated the architectural world, sustaining continuous engineering developments that refined their typology (Fig. 2c). Nonetheless, in essence, the same structural model is being reproduced over the years: a metal load-bearing structure, cladded with glass. Technological developments in the field of structural glass during the last three decades, however, showcased in smaller scale structures, the functional and aesthetical benefits of maximized transparency and light income (Fig. 2d), as these result from employing float glass as the structural element and minimizing, if not omitting, the use of steel. This can be achieved by taking advantage of the high compressive strength of glass, yet the two-dimensionality of float glass imposes buckling-related limitations and shaping challenges, which prevent the realization of larger-span all-glass curved structures. In this context, cast glass could be an excellent candidate for achieving compressive, fully transparent curved structures of larger spans, as with casting, robust components of complex geometry and considerable thickness can be achieved. Yet, the use of cast glass as a structural material is still in an experimental phase; lack of manufacturing, quality control and engineering norms coupled with a lack of design data, prevents its use in structural applications. Therefore, its suitability in such structures has been so far tested in small-scale realized projects, and with prototypes that evaluate the casting ease, mechanical performance and assembly method of the cast components. This paper explores several realised case studies of small-scale, cast glass arches, vaults and domes where the TU Delft Glass Research Group was involved, addressing the following main points:

(i) manufacturing challenges: in this case, the strategy for achieving the desired curvature of the structure is addressed in relation to the shaping limitations of cast glass, the resulting number of different component shapes and moulds, and the requirements for post-processing.

(ii) assembly methods: the choice of a permanent or temporary adhesive bonding versus a dry-assembly solution by using interlocking components and dry-interlayers is discussed. Where applicable, the output from the mechanical validation of the assembled glass system is provided.

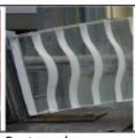
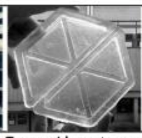
(iii) construction ease: insights on the assembly method and sequence are provided, covering a range of solutions from scaffolding and layer-by-layer building, to rotating frames and robotic arms.

Figure 2. The evolution of (large-span) glass roofs and the increase of the glass-to-steel ratio: (a) Oxford University Museum of Natural History, 1861, (b) Palm House at Kew Gardens, 1848, (c) Queen Elizabeth II Great Court at the British Museum, 2000, and (d) Davies Alpine House at Kew Gardens, 2006.

2. Case studies

Table 1 provides an overview of cast glass arch, vault and dome structures that have been developed and -in cases- realised, with the involvement of TU Delft. Different aspects concerning the manufacturing process, assembly method and construction solution followed for each specific project are discussed below.

Table 1. Overview of cast glass case studies comprising arch, vault, or dome structures.

Case study details	Project name & location	Crystal Houses, Amsterdam	Glass Masonry Bridge, Delft	LightVault, London	Qaammat Pavilion, Greenland	Geodesic cast glass dome	Glass Vaults	The Glass dome
	Credits & sources	MVRDV, TU Delft, abt [1, 2]	TU Delft [3-6]	SOM, Princeton, TU Delft [8-11]	Konstantin Arkitekter, TU Delft [12-13]	TU Delft [14]	TU Delft [15-16]	TU Delft [17]
	Status	Realised	R&D	Realised	Realised	Case study	Case study	Case study
	Structure type	Arched architrave	Arch	Vault	Semi-circular walls, inclined, perforated	Dome	Vault	Shallow dome
	Structure size (LxWxH, m)	[1.26 (window), 1.89 (door)]x0.21x0.33	14.08x2.2x1.1	2.6x1.6x2	≈3.2x3.7x2	ø20x10	16.5x10.3x2.4	ø35.97x7.45
	Image							
Manufacturing	Component shape	Rectangular, tapered	Rectangular, tapered, 1 curved interlock	Rectangular	Rectangular	Trapezoid, pentagon, ribbed	Triangle with tongue/groove interlock, spherical node	Double sphere
	Component size (LxWxH, mm)	(58-62)x210x(44-215)	100x162x350	Main: 246x116x53 Half: 123x116x53	Main: 246x116x53, corner: 121x116x53	(440-520)x(940-1000)x96	(330-782)x(330-782)x100, ø258	220x125x92
	no. of different components	22 (window)+ 32 (door)+ 5 (corner)	1 + 2 (corner)	1+1 (half)	1 + 1 (corner)	20	1249 interlocking triangles, 1 node	1
	Production Method	Hot pouring	Hot pouring	Hot pouring	Hot pouring	Kiln-casting	Kiln-casting	Kiln-casting
	Mould type	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Silica-plaster investment	Silica-plaster investment based on wax models cast with adjustable mould	Silica-plaster investment
	Post-processing	CNC grinding & polishing	None	None	None	Grinding	Grinding	Grinding
Assembly method	Bonding type	Adhesive	Interlocking, dry interlayer	Adhesive	Adhesive	Adhesive	Interlocking, dry interlayer	Interlocking, dry interlayer
	Bonding characteristics	UV-curing acrylate (DELO 4468)	Polyurethane rubber sheet	2 component multi-purpose epoxy putty (PIG™)	2-component polyurethane adhesive (3M™ DP 610), 2-component structural silicone (Dowsil Exp.)	UV-curing acrylate (DELO 4494)	Rubber dry interlayer	TPU dry interlayer
	Joint thickness (mm)	0.25	1	≤20	1 (3M), 2-3 (DOW)	1	3	2
	Validation method	Applicability tests, 4-point bending	Mid-span loading, shear test	Applicability tests, full scale mock-up	Applicability tests, full-scale mock-up	Component mock-up	Component mock-up	Component mock-up
Construction ease	Assembly method	Prefabricated with rotating mould	Dry assembly on site	Construction with 2 robotic arms	Row by row bricklaying	Row by row bricklaying	Row by row bricklaying	Row by row bricklaying
	Scaffolding on site	Not required	Required	Not required	Not required	Required	Required	Required

2.1. Crystal Houses Façade

The Crystal Houses façade in Amsterdam, designed by MVRDV, is a reinterpretation of the original 19th century brick façade in cast glass. As such, 12 architraves, 10 to be placed over the windows (1.26m span) and 2 larger ones over the doors (1.89m span) were designed, following the same structural system of the cast glass façade (Fig. 3d). This system comprises cast glass components (produced by Poesia) bonded brick by brick on site, using a stiff, transparent UV-curing acrylate of 0.25mm thickness [1]. The selected adhesive, due to its low viscosity, was applied at the horizontal brick surfaces only; vertical application would lead to non-homogeneous results due to the downward flow of the adhesive prior to curing. In addition, due to the adhesive's minimum optimum thickness, extreme dimensional precision had to be met, dictating, among others, the CNC grinding and polishing of the bricks to meet the desired tolerances [1]. Realizing the architraves was therefore an additional challenge, as (i) the cast glass bricks had to be tapered and bonded to precision to reproduce the exact curvature, (ii) the top side of the architraves had to be perfectly straight –within the 0.25mm tolerance range- to accommodate the glass brickwork above, and (iii) the adhesive could not be applied on site, as this would imply its vertical application. To solve the above challenges, 54 different steel moulds were required to achieve the desired geometry of the tapered bricks (544 pieces in total), and the vertical surfaces of the bricks were further CNC-post processed to meet the tolerances. The architraves were then prefabricated at the TU Delft Glass lab, using a rotating steel frame that allowed the horizontal application of the adhesive at every brick layer, and the creation of a straight line at the top side of the architraves (Fig. 3a,b). The prefabricated components were then craned on site, and special corner brick pieces (five per side) were adhesively bonded one by one to the side of the architraves to keep it in place (Fig. 3c). To ensure that the architraves could withstand their own weight before becoming incorporated in the wall system, a destructive 4-point bending test was conducted in a door architrave specimen. The specimen failed at 6.7MPa [2], withstanding 41.6KN which was more than double of the service load specified by the project engineers (abt).

Figure 3. Cast glass architraves for the Crystal Houses Façade: (a, b) rotating steel frame ensuring for the horizontal application of the UV-curing adhesive and for achieving a straight surface at the top of the architrave, (c) the architraves were temporarily rested on a steel frame until the surrounding wall bricks were adhered, (d) final result of the façade (image credits: MVRDV)

2.2. Glass Masonry Bridge

The Glass Masonry Bridge (Fig. 4a, non-realized project) is a pedestrian bridge designed for the TU Delft campus [3]. The arch-formed bridge consists of cast, interlocking glass components, dry assembled with a polyurethane (PU) rubber interlayer inbetween. One main component (Fig. 4b) is used -of a slightly tapered geometry to achieve the desired curvature- while two different corner components are designed to connect the bridge with the foundations. To reduce the complexity and costs of the production process, the post-processing of the glass surfaces is avoided, and dimensional deviations are expected to be absorbed by the rubbery interlayer. Several interlocking geometries were tested based on their interlocking performance [3, 4] but also on the complexity of the casting process and the compatibility of the geometry to the glass properties (e.g. sharp angles were avoided). A smooth, curved interlock was opted and validated by testing kiln-cast specimens (1:2 scale) in shear [5] (Fig. 4c) and compression [4]. These experiments indicated that poor contact between the interlocking surfaces can lead to the generation of point loads and subsequent fracture. A larger specimen (1m span), comprising components (1:2 scale) that were waterjet cut out of cast glass bricks, was tested in bending (Fig. 4d), showing satisfactory shear resistance, yet further testing involving a larger span and different load combinations is required [6]. For the assembly of the Glass Masonry Bridge, a secondary Glass Truss Bridge has been constructed below, to serve as scaffolding [7].

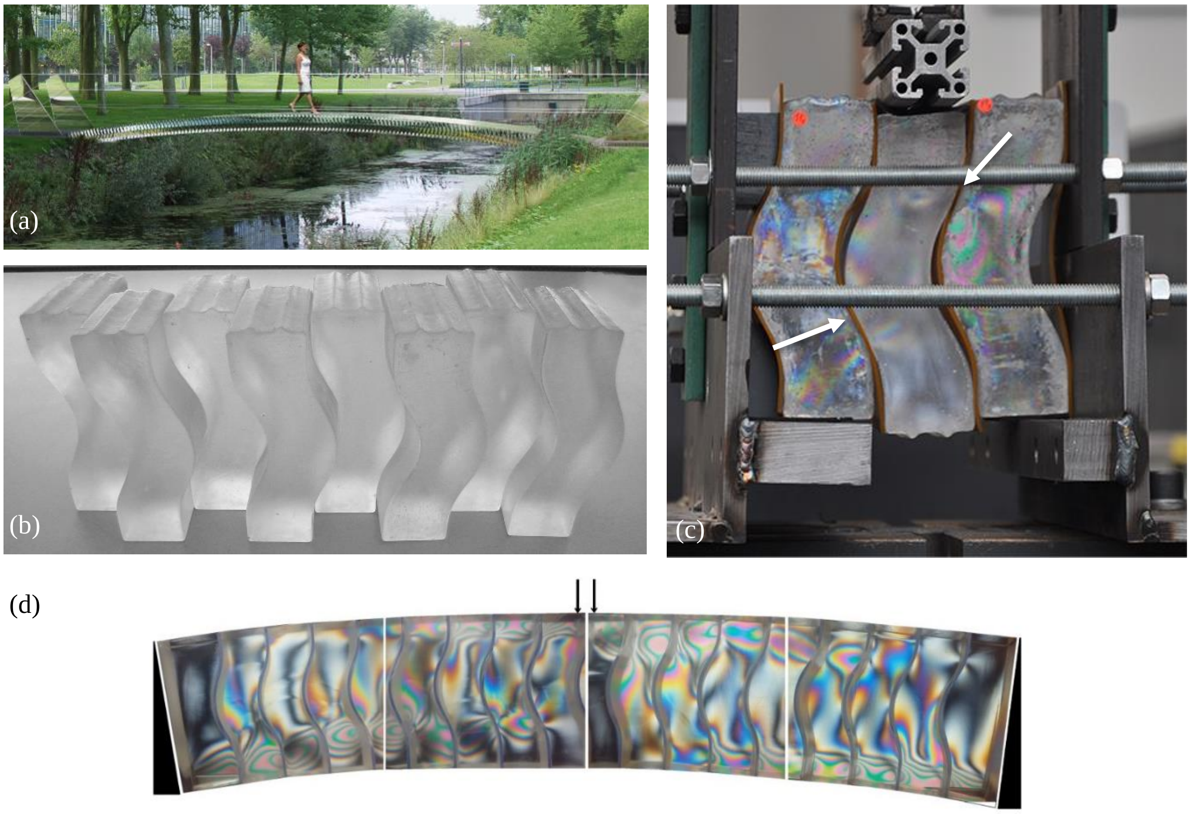


Figure 4. Cast Masonry Bridge: (a) 3D-visualization of the bridge, (b) kiln-cast glass components in 1:2 scale, showing the interlocking principle, (c) testing in shear combined with photography using cross-polarized light indicated the generation of point loads instead of the full cooperation along the interlocking surface, (d) photograph using cross-polarized light of a loaded 1m arch segment made from waterjet-cut components out of cast glass bricks.

2.3. LightVault

The LightVault, designed by SOM and Princeton University c.r.e.A.te lab and Form Finding Lab, is a double curved glass brick vault following a herringbone pattern [8]. It was designed to be built without the use of scaffolding, but with the aid of two robotic arms that would place the bricks in the precise location (Fig. 5a). The structure is realized in its majority with the use of one type of rectangular, non-tapered cast glass brick (309 pieces, produced by Poesia) that is not post-processed after casting, while a small number of half-sized bricks (29 pieces) are strategically inserted to reduce the occurring gaps in the structure. Nonetheless, due to the use of one rectangular geometry and taking into account the dimensional deviations occurring from casting, wedge-shaped gaps of significant thickness between the brick interfaces were created, the majority of which were optimized to be below 17.5mm [9]. A fast curing Epoxy Patty of 20mm gap-filling capability was selected as the intermedium [9, 10], minimizing the time the robotic arm would hold the brick in place to 12-15min (25min for the middle arch) [11]. Several prototypes were constructed to evaluate the assembly order, suggesting that the building of a broader brick wall section at the base, would enhance the temporary stability of the system (Fig. 5b, c).

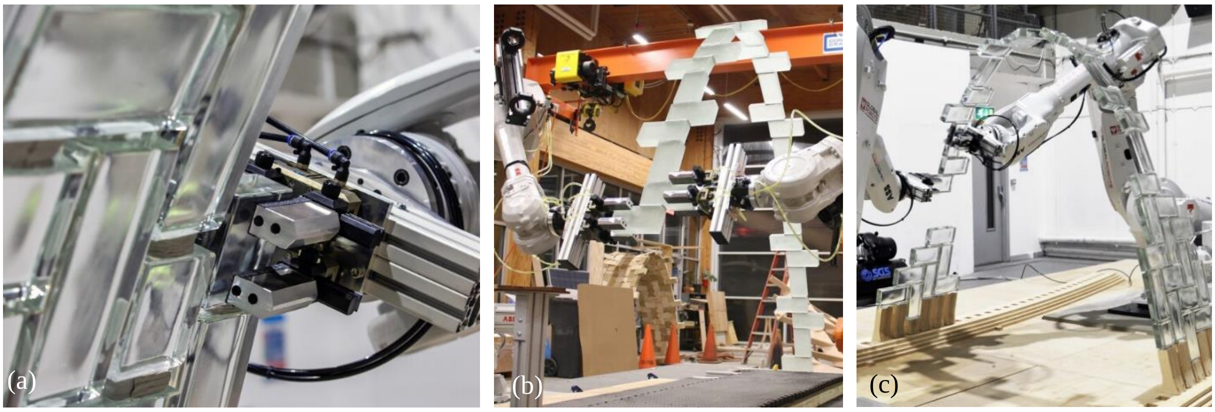


Figure 5. Robotically assembled cast glass vault: (a) robotic arm placing a half-sized glass brick (image credits: M. Grzeskowiak/SOM), (b) unstable assembly configuration (image credits: I. X. Han/ Princeton University), (c) redesigned assembly order to ensure the temporary stiffness of the system (image credits: I. X. Han & E. Bruun, Princeton University).

2.4 Qaammat Pavilion

The Qaammat Pavilion in Greenland, designed by Konstantin Arkitekter, comprises two semi-circular, perforated walls that follow a frustum shape (Fig. 6a, c). The walls were constructed with the use of a basic rectangular cast glass brick (1100 pieces) and a limited amount of half-sized bricks for the edges (bricks produced by Wonderglass). The bricks were not post-processed and were adhered with two different types of 2-component adhesives. At the bottom rows, where larger gaps between the bricks occur due to the developed geometry, a clear polyurethane of high stiffness, >3.7MPa shear strength and 1mm gap-filling capacity was selected [10, 12]. For the middle and top rows, where less stresses are developed but also higher deviations are built up from the occurring variations at the bricks' height due to casting, a more flexible, white structural silicone of 2-3mm gap filling capacity and circa 1MPa shear strength was applied, developed by DOW specifically for this project [13]. The bricks were laid row by row with the aid of CNC-cut PVC templates that would control their placement (Fig. 6b). The use of scaffolding was avoided by selecting 2-component, fast curing adhesives, which reach their set-time within 4-20min. To ensure the temporary fixing of the bricks until the set-time is reached, double-sided tape spacers were placed between the bricks, holding them in position and securing the desired thickness of the adhesive layer.

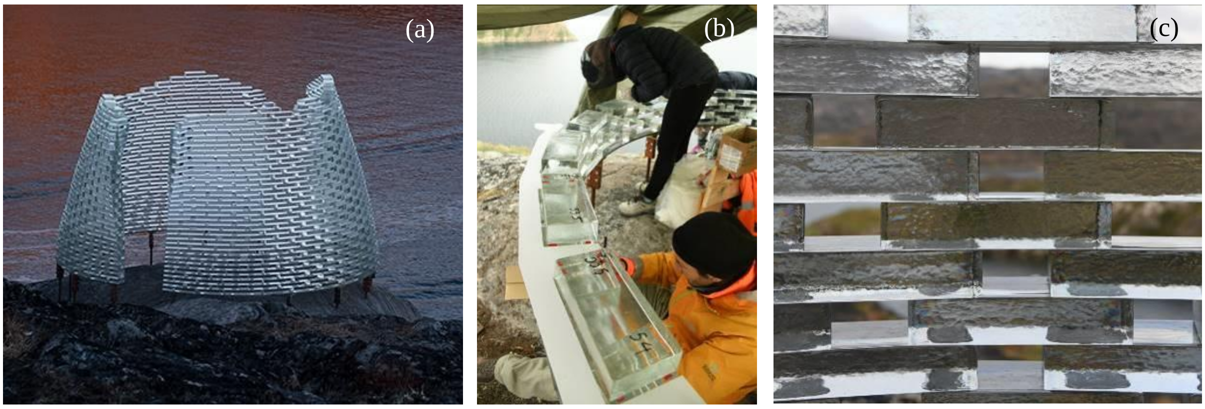


Figure 6. The Qaammat Pavilion in Greenland: (a) Aspect of the finalized project (Image credits: Julien Lanoo), (b) row by row brick laying on site, using PVC templates, (c) detail of the perforated cast glass wall.

2.5 Geodesic cast glass dome

This dome is a theoretical study on how to achieve the minimum number of different components to realize a 20m span cast glass dome [14]. The components should not overly exceed a maximum mass of 10kg, to ensure a realistic annealing time during casting, and to facilitate the assembly process. To fulfil the above criteria, Buckminster Fuller's Geodesic dome configuration was preferred versus a horizontal ring division. Using a geodesic dome frequency of 22, 20 different pieces are required; 19 hexagons and 1 pentagon. To further reduce the mass, the pieces were divided in half, and a ribbed geometry was preferred instead of a constant thickness (Fig. 7a, b). The pieces were slightly tapered and adhered together with a UV-curing acrylate that could accommodate up to 1mm tolerances. A scaffolding would be required for the construction of the dome. Prototyping of the components in 1:5 scale was conducted, to evaluate the suitability of the designed shape in relation to the casting process (Fig. 7b). Larger bevel angles are advised for the rib edges.

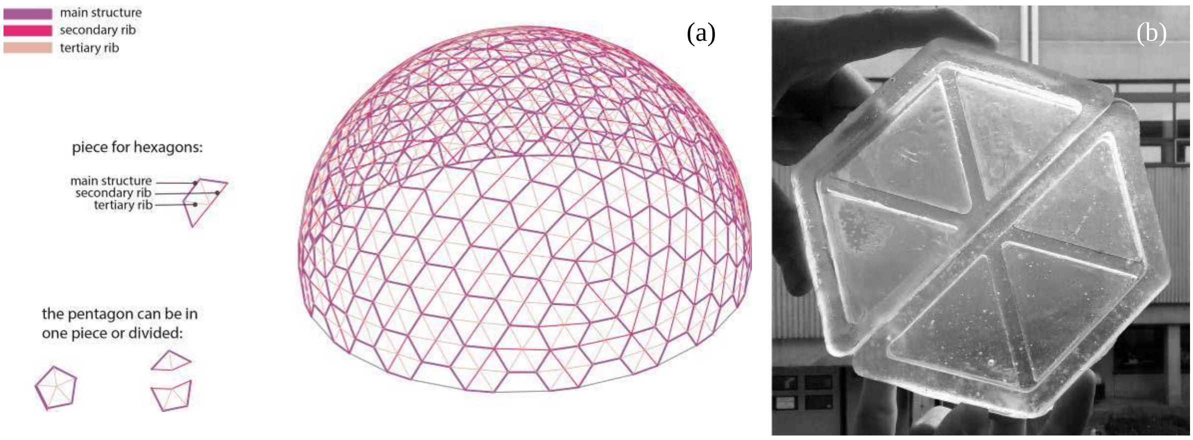


Figure 7. Concept for a cast glass geodesic dome: (a) division of the components and distinction of rib thicknesses, (b) 1:5 kiln-cast glass mock-up.

2.6 Glass Vaults

This project studies the realization of free-form transparent shell structures, by employing interlocking cast glass voussoirs [15, 16]. The voussoirs interlock thanks to their tongue or groove -shaped side surfaces, and the pieces are dry-assembled with the use of a rubber interlayer in between. Node components are also introduced at the intersection points of the voussoirs. To achieve such a complex system, voussoirs of distinct geometries are required. Adjustable moulds in triangular, quadrangular and hexagonal configuration (Fig. 8a) are therefore devised that adjust the length and angles of the components' edges, and the type and angle of the interface geometry (tongue or groove). As a proof of concept, a shell roof structure is designed for the courtyard of the Armamentarium in Delft (Fig. 8c), and an algorithm is developed to tessellate the double-curved surface into triangular components, and to assign the interface types and angles for each component. 1250 pieces are designed, varying in mass from 5.4 to 38.5kg, and with an average mass of 24.6kg. The node pieces are identical and require one mould only. The ability of the mould to adjust to the generated designs was further tested by constructing distinct models of voussoirs in wax. These wax models were thereafter used to produced investment moulds for kiln-casting the voussoirs in glass (Fig. 8b).

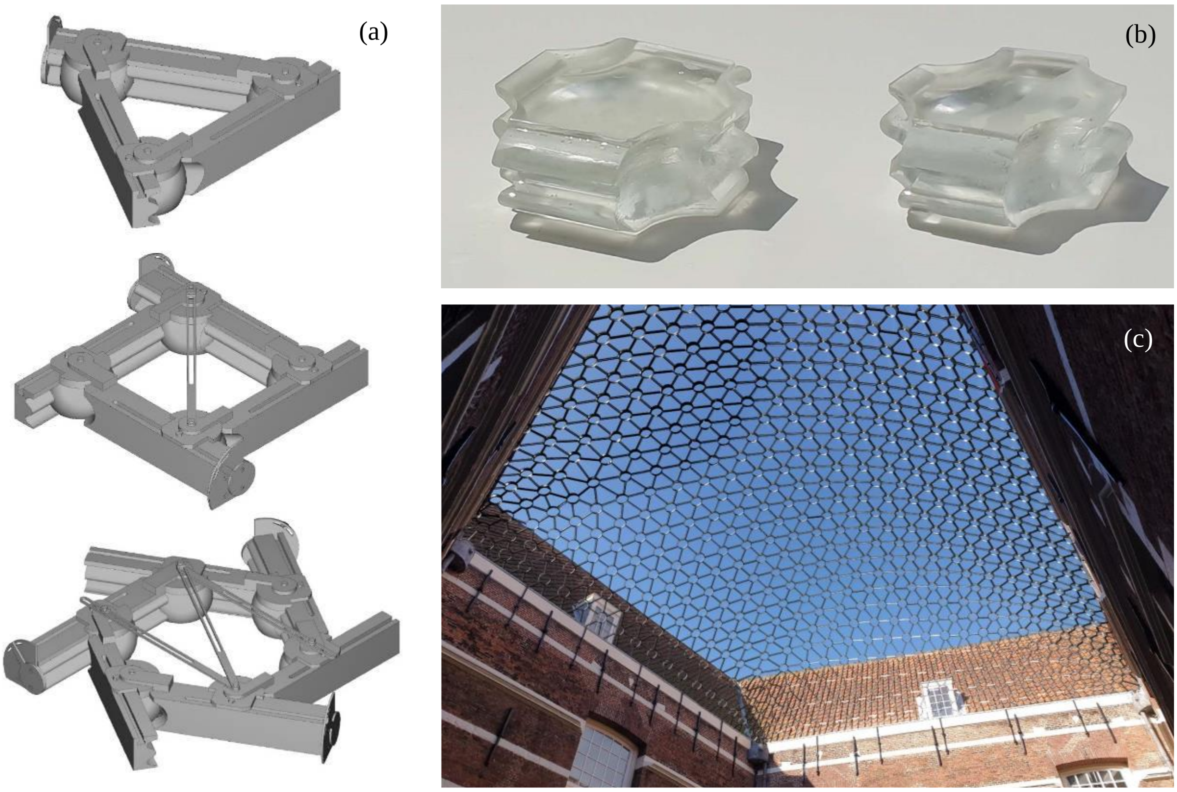


Figure 8. Concept for achieving free-form interlocking glass shell structures: (a) adjustable mould system in triangular, quadrangular and hexagonal configuration, (b) kiln-cast voussoirs using investment moulds produced with the lost-wax technique; the wax models were produced from adjustable moulds, (c) case study of a free-form shell out of interlocking cast glass components, designed to cover the courtyard of the Armamentarium in Delft.

2.7. The Glass dome

The Glass dome aviary project studies the construction of a dry-assembled cast glass dome using one omnidirectional interlocking component [17] (Fig. 9a). The component is designed by blending three spheres of different size (Fig. 9d), ensuring an interlock in both ring (horizontal, Fig. 9c) and arch (vertical, Fig. 9b) direction. The component has a 2.5kg mass, facilitating the annealing process during casting, and the assembly process. Thermoplastic polyurethane (TPU) interlayers, produced by compression molding, are placed between the glass components both in arch and ring direction. The interlayers in arch direction are identical, while those in ring direction differ in each row due to the changing curvature. A wooden substructure is suggested for assembling the dome, after which a customized compressive steel ring is fixed at the top, while a tension ring is applied at the bottom. To validate the castability and validity of the design, five components were kiln-cast in 1:2 scale (Fig. 9e). Challenges with air-entrapment were identified due to the enclosed mould design, and the introduction of mould vents is suggested to prevent the encountered problem.

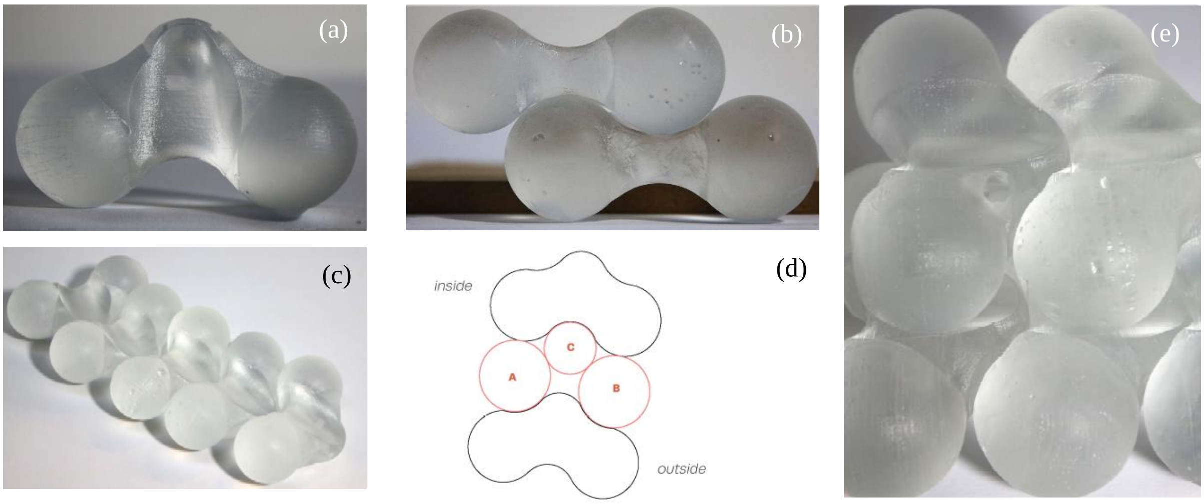


Figure 9. Omnidirectional interlocking cast glass component for a dome structure: (a) top view of the component, (b) array of the components along the arch direction, (c) array of the components along the ring direction, (d) design of the component based on 3 spheres of distinct dimensions to ensure interlock in both horizontal and vertical direction, (e) assembly of the components in both ring and arch direction.

3. Design guidelines

The presented case studies show the design choices made regarding the shape, mass and number of different components, the type of bonding (permanent, interlocking), and the method of assembly, in order to realize the desired curved cast glass structures. Based on this experience, and in combination with basic principles applied to the casting process [18], design guidelines can be developed for future applications. The main design choices are discussed below and presented in Figure 10:

Regarding the general shape of the structure, this should be principally working in compression, to benefit from the high compressive strength of glass. Double-curved, asymmetric geometries increase by definition the number of different components, and normalization of the shape is advised to prevent a plethora of distinct pieces that strain the production process and delay the assembly. Nonetheless, in case of complex geometries, two options are worth considering regarding the design of the component:

(i) using one global geometry and solving the tolerances in the interface. This interface can be an adhesive of high gap-filling capacity (e.g. an epoxy patty) or a stiff, customized dry interlayer (e.g. 3D printed plastic pieces)

(ii) using distinct components produced by adjustable moulds, to reduce the production costs.

In parallel, the bonding strategy between the components needs to be determined. Adhesively bonded structures can be very stiff –based on the adhesive type and bond thickness, but lead to permanent, non-dismountable solutions. Dry-interlocking systems, although less stiff, promote circularity, but also increase the casting complexity; high-precision of the interlocking interfaces is required to achieve homogeneous transfer of the load and thus avoid peak stresses, which increases the production costs. In both cases, the redundancy of the system should be evaluated, ensuring a safe structure even in the event of breakage of a few components. As structural norms and guidelines on the design and calculation of such cast glass structures do not exist, mechanical testing of characteristic mock-ups of the system is necessary, to validate the dimensioning of the structure and the choice of interface material.

Regardless of the solution path selected, several guidelines should be followed for the design of the cast glass components. The mass of each component desirably should not exceed a maximum of 10kg, to reduce the annealing time during the casting process, but also to facilitate the handling of the piece during assembly. To further facilitate the annealing process, abrupt changes in thickness along the piece should be avoided, while sharp edges are also not favourable in terms of casting and construction. Organic, spherical geometries are favourable in terms of annealing, but require closed or press-moulds; careful introduction of vents in those moulds should prevent air-entrapment defects at the surface of the glass components.

Some form of scaffolding is –in most cases- unavoidable, yet, the use of robotic arms is a proven solution for avoiding scaffolding in adhesively bonded double-curved systems. For achieving configurations of high-precision, the preassembling of segments of the structure (again adhesively bonded system) with the use of frames and guides should be considered. Lastly, for minimizing the scaffolding requirements, the brick-by-brick laying per row and the (almost) horizontal application of a fast curing adhesive should be opted for.

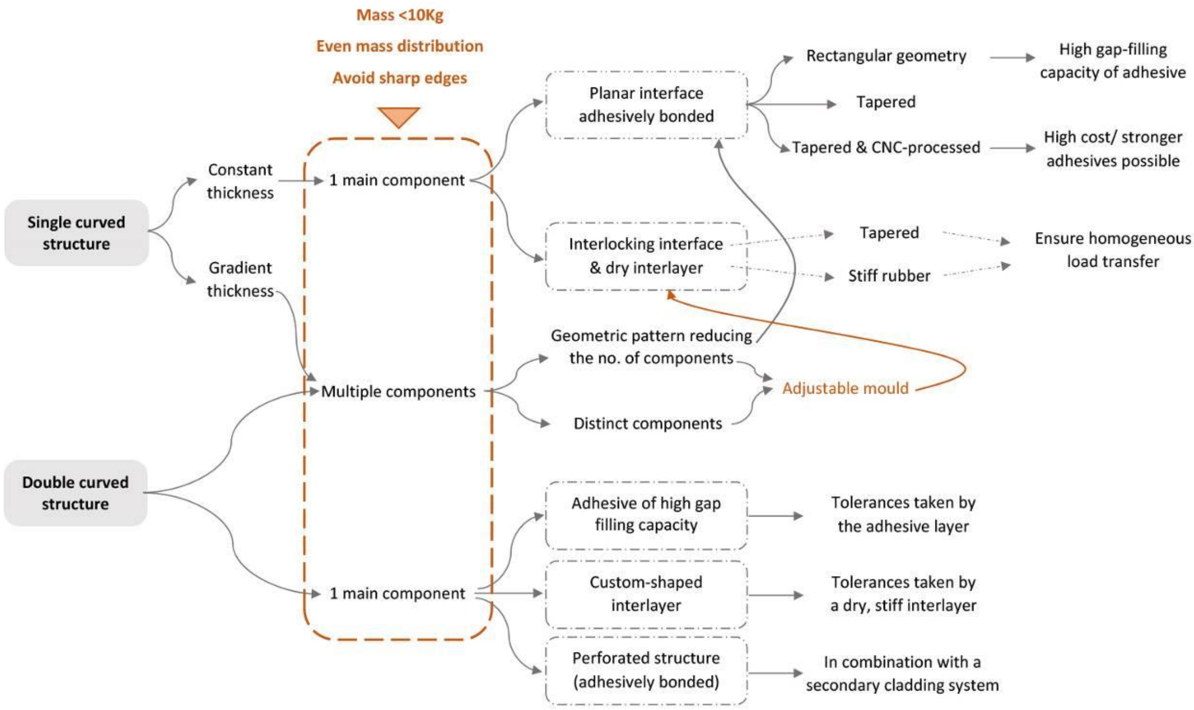


Figure 10. Design selections for achieving single and double curved cast glass structures.

4. Conclusions

Although cast glass is an excellent candidate for materializing strong and transparent arch, vault and dome structures, realized structures using cast glass components are rarely seen. Discouraging factors responsible for this include the lack of engineering data, coupled with the complexities imposed on the casting process due to the (double) curved geometries and the associated high costs. From the studying of a few realized case studies and theoretical projects, guidelines arise concerning the choices to be made on the design of the component, the connection method and the assembly process. These evolve around the decision of absorbing the tolerances at a component level –resulting to multiple different shapes- or at the interface –leading to either thick adhesive layers or custom-shaped dry interlayers. The choice of an adhesive medium versus a dry rubber interlayer has further consequences on the stiffness, demountability, and allowable tolerances of the system. The casting parameters play the most crucial role, as the reduction of the number of different moulds, the reduction of the mass, and the avoidance of post-processing, all work towards the reduction of the production costs and time, making the structure more feasible. Experimental validation of a mock-up of the chosen system is always required for ensuring a safe structure.

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