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Lessons learned from large-scale castings and state-of-the art load-bearing cast glass in architecture

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The potential of cast glass in structural applications. Lessons learned from large-scale castings and state-of-the art load-bearing cast glass in architecture

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ABSTRACT

This paper investigates the potential of cast glass structural components in architectural applications. Initially, the commonly applied casting methods, glass types and mould types are discussed. To address both the possibilities and limitations in the size and form of cast glass components, an overview of the largest monolithic pieces of cast glass ever made is presented, from giant telescope mirrors and nuclear glass blocks to massive artifacts. Weighing several tons each, these cast glass pieces are assessed with comparative charts of technical data collected from literature, industry and field research, regarding their geometry, materialization, manufacturing method and annealing process. The data highlight not only the potential but also the practical implications involved due to the meticulous and time-consuming casting and annealing process of three-dimensional glass elements. Learning from the extreme, proposals are made for optimizing the size, shape and casting process of cast glass components suitable for architectural applications. Subsequently, the state-of-the-art architectural examples employing cast glass are analyzed and evaluated in terms of manufacturing, structural system, level of transparency, ease of assembly and disassembly. Based on the findings the authors suggest new design concepts for cast glass components that can take full advantage of the glass' properties and can result in novel, transparent, yet load-bearing architectural applications.

1. Introduction

Advancements in glass technologies and engineering over the last 30 years have changed the way we conceive glass. Combining transparency, durability and a compressive strength higher than that of concrete and even steel, glass has evolved in the engineering world from a brittle, fragile material to a structural component of high compressive load-carrying capacity. From the revolutionary application of glass as a structural skin in greenhouses to the full glass structures (Fig. 1) of EOC engineers [1], glass's structural boundaries have been continuously stretching in the quest of maximum transparency [2]. The glass sheets are becoming larger and the connections less, both in size and number [3]. The long pursued architectural desire for a totally transparent, almost dematerialized, structure is finally feasible.

Still, due to the prevalence of the float glass industry, the design of full-glass structures is dominated by the limited forms, shapes and dimensions feasible by virtually two-dimensional, planar elements: either orthogonal or cylindrical in shape and supported by glass fins and beams or braced against buckling using slender, non-glass components.

Cast glass can escape the design limitations imposed by the virtually two-dimensional nature of float glass. By pouring molten glass into moulds, solid three-dimensional glass components of considerably larger cross-sections and of virtually any shape can be obtained. Owing to their monolithic nature, such components can form repetitive units for the construction of three-dimensional, self-supporting glass-structures that do not buckle due to slender proportions, sparing the necessity of additional supporting elements [4]. Indeed, solid cast glass components are a promising solution for engineering pure glass structures of high transparency (Fig. 2) that take full advantage of glass's compressive strength; a solution little explored so far.

Discouraging factors such as the meticulous and time-consuming cooling process and the corresponding high manufacturing costs, have restrained cast glass to only a few erected architectural applications. Still, cast glass has manifested its full potential in the fields of

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Fig. 1. The Apple Store in New York by EOC Engineers.

Fig. 2. The Crystal Houses façade by MVRDV Architects, made of adhesively bonded glass blocks. Image credits: Daria Scagliola and Stijn Brakkee.

astronomy, nuclear power and art, where monolithic multi-ton components are realized. Such applications, even though indirectly related to architecture, can set the basis for comprehending not only the capabilities but also the challenges involved in casting considerable masses of glass.

This paper investigates the potential of cast glass structural components in architecture. An outline of the commonly applied casting methods, glass types and mould types is provided in chapter 2. Following, chapter 3 presents an overview of the largest monolithic cast glass pieces, demonstrating both the limitations and potential of cast glass. Characteristic examples are assessed with comparative technical data charts regarding their geometry, materialization, manufacturing and annealing process. Based on the findings, proposals are made for the further development of glass components suitable for structural applications in architecture. In chapter 4, the state-of-the-art examples structurally employing cast glass in architecture are studied and assessed by criteria such as ease of manufacturing and assembly and applied structural system. Based on all the above, in chapter 5, the authors propose new design concepts for cast glass components that fit the characteristics and peculiarities of cast glass as a construction

Table 1
Approximate chemical compositions and typical applications of the different glass types as derived from [5].

Glass type	Approximate composition	Observations	Typical applications
Soda-lime (window glass)	73% SiO_2 17% Na_2O 5% CaO 4% MgO 1% Al_2O_3	Durable. Least expensive type of glass. Poor thermal resistance. Unacceptable resistance to strong alkalis	Window panes Bottles Façade glass
Borosilicate	80% SiO_2 13% B_2O_3 4% Na_2O 2.3% Al_2O_3 0.1% K_2O	Good thermal shock and chemical resistance. More expensive than soda-lime and lead glass.	Laboratory glassware Household ovenware Lightbulbs Large telescope mirrors
Lead silicate	63% SiO_2 21% PbO 7.6% Na_2O 6% K_2O 0.3% CaO 0.2% MgO 0.2% B_2O_3 0.6% Al_2O_3	Second least expensive type of glass. Softer glass compared to other types. Easy to cold-work. Poor thermal properties. Good electrical insulating properties.	Artistic ware Neon-sign tubes Television screens Absorption of X-rays (when PbO % is high)
Aluminosilicate	57% SiO_2 20.5% Al_2O_3 12% MgO 1% Na_2O 5.5% CaO	Very good thermal shock and chemical resistance. High manufacturing cost.	Mobile phone screens fiber glass High temperature thermometers Combustion tubes
Fused-silica	99.5% SiO_2	Highest thermal shock and chemical resistance. Comparatively high melting point. Difficult to work with. High production cost.	Outer windows on space vehicles Astronomical telescopes
96% silica	96% SiO_2 3% B_2O_3	Very good thermal shock and chemical resistance. Meticulous manufacturing process and high production cost.	Furnace sight glasses outer windows on space vehicles

material and can result in transparent, load-bearing architectural applications.

2. Cast glass: materials and production methods

2.1. Types of glass

Based on its composition, commercial glass can be divided into six main families/types: Soda-lime, borosilicate, lead, aluminosilicate, 96% silicate and fused silica glass. Table 1 presents the typical chemical composition and characteristic applications of each glass type.

Soda-lime is the most common and least expensive glass type [6]. It features limited resistance to high temperatures and to rapid temperature fluctuations. Borosilicate glass, i.e. silicate glass with minimum 5% boric oxide, has a comparably lower thermal expansion coefficient providing resistance to thermal shocks and reduced annealing time. Lead glass has a high percentage of lead oxide (min. 20% of the batch) and is relatively soft. It has a lower working temperature than soda-lime and is the second least expensive option. It is favoured for cast glass art as it is much softer to grind and polish than soda-lime [7]. On the downside lead glass has limited resistance to thermal shocks and high temperatures and is susceptible to scratching. Aluminosilicate glass, 96% silica glass and fused silica glass can sustain much higher operating temperatures and heat shocks than borosilicate glass; however, they are more difficult to fabricate due to the considerably higher melting temperatures required (Table 2), which in turn increases substantially the manufacturing cost. Thus, they are used in specialized applications, such as mobile screens (aluminosilicate) and spaceship windshields (fused-silica) [8].

Owing to their reduced cost and comparatively easier manufacturing process and post-processing, soda-lime, borosilicate and lead glass are currently prevailing for castings of standardized or large monolithic glass objects.

2.2. Casting process

According to the starting state of glass, glass casting can be divided into primary and secondary casting. In primary casting, glass is founded as a hot liquid from its raw ingredients, whereas in secondary casting, glass already made in solid pieces (i.e. sheet, rods, marbles, grains, powder) is re-heated until it can flow and be shaped as desired [10]. Thus, the secondary process requires lower operating temperatures compared to those for founding glass.

Accordingly, the main process of primary casting is hot-forming (melt-quenching) and of secondary casting is kiln-casting (Fig. 3). The principal difference between the two methods, besides the initial state of glass, is the required infrastructure. Kiln-casting employs a single kiln for the melting of the (already formed) glass into the moulds and for the subsequent annealing process [11]. In contrast, in hot-forming, molten glass from a furnace is poured into a mould and is then placed in another, second furnace for annealing.

In both methods, the annealing process is similar. Oikonomopoulou et al., (2017) [12] provides a good description of the annealing process: Initially glass is heated until it is molten enough[1] to flow into the mould. Once the mould is filled, the glass is rapidly cooled to a few degrees below its softening point. This rapid cooling stage (quenching) is essential for preventing a crystal molecular arrangement of the melt. During this phase, the glass's relatively low viscosity allows any induced thermal stress to relax to a negligible amount immediately [13]. When the glass temperature drops below its softening point, the viscosity of glass is sufficient for it to retain its shape and not deform under its own weight [14]. At this point, the annealing process of the object starts, aiming at eliminating any possible differential strain and preventing the generation of internal residual stresses during further cooling.[2] The cast glass should be maintained for adequate time at the annealing point to release any existing strains and then cooled at a sufficiently slow rate to prevent the generation of residual stresses when the glass temperature has reached equilibrium [5]. Effectively, below the strain point, stress is unable to relax in time and is considered permanent [15]. When the temperature of the entire object has dropped below the strain point, it can cool at a faster pace until ambient temperature, yet adequately slow to avoid breakage due to thermal shock [5].

During the annealing range, the magnitude of the resulting internal stresses is largely determined by the temperature difference between the warmest and coolest parts of the glass, its coefficient of expansion and the thickness of the section [5]. Accordingly, round or ellipsoid shapes and equal mass distribution are key aspects for the prevention of residual stresses and are thus preferred over sharp, pointy edges where internal residual stresses can concentrate due to inhomogeneous shrinkage.

Nonetheless, in practice, the necessary heat transfer for achieving the desired temperature difference is influenced by various factors, challenging to accurately simulate, such as: the element's shape and mass distribution, its sides exposed to cooling, the amount of other

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[1] The viscosity of the glass at that point is expected to be between 10 and 10^3 Pa s, defined as melting point and working point of glass correspondingly [9].

[2] At this point, in the hot-pouring method the cast object is placed into the annealing oven.

Table 2
Approximate properties of the different glass types of Table 1 based on [5].[a] Mean melting Point at 10 Pa.s as stated by [9].

Glass type	Mean melting Point at 10 Pa.s** [°C]	Soft. Point [°C]	Anneal. Point [°C]	Strain Point [°C]	Density Kg/m^3	Coeff of Expan. 0–300 °C 10–6/°C	Young's Modulus GPa
Soda-lime (window glass)	1350–1400	730	548	505	2460	8.5	69
Borosilicate	1450–1550	780	525	480	2230	3.4	63
Lead silicate	1200–1300	626	435	395	2850	9.1	62
Aluminosilicate	1500–1600	915	715	670	2530	4.2	87
Fused-silica	> > 2000	1667	1140	1070	2200	0.55	69
96% silica	> > 2000	1500	910	820	2180	0.8	67

[a] These values are only given as a guideline of the differences between the various glass types. In practice, for each glass type there are numerous of different recipes resulting into different properties.

Fig. 3. Left: Primary casting method (hot-forming). Right: Secondary casting method (kiln-casting).

Table 3
Characteristics of prevailing mould types for glass casting.

Characteristics	Mould type						
Reusability	Disposable		Permanent				
Material	Silica Plaster	Alumina-silica fiber	Steel/Stainless steel			Graphite	
Adjustability	–	–	Adjustable	Fixed	Pressed	Adjustable	Fixed
Production method	Investment casting/lost-wax technique	Milling	Milling/cutting and welding			Milling/ grinding	
Manufacturing costs	Low	High	Moderate to high			High	
Top temperature	900–1.000 °C	≈ 1.650 °C	≈ 1.200 °C/1.260 °C			unknown	unknown
Glass annealing method	Mould not removed for annealing		Mould usually removed for annealing but can also remain if high accuracy is required			Mould removed for annealing	
Release method	Immerse in water	Water pressure	Release coating necessary (ex. Boron Nitride)			Release coating necessary	
Level of precision	Low/moderate	High	Moderate/ High	High	Very high	Moderate/ High	High
Finishing surface	Translucent/ rough	Translucent/ rough	Glossy. Surface chills may appear if the mould is not properly pre-heated			Glossy with surface chills	
Post-processing requirements	Grinding and polishing required to restore transparency and increase accuracy		Minimum or none post-processing required			Minimum to moderate post-processing required	
Applicability	Single component/low volume production		High volume production			High volume production	

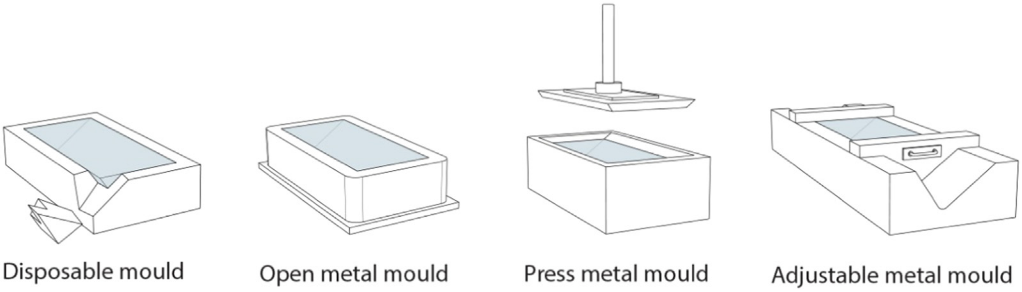

Fig. 4. Illustration of the most common mould types.

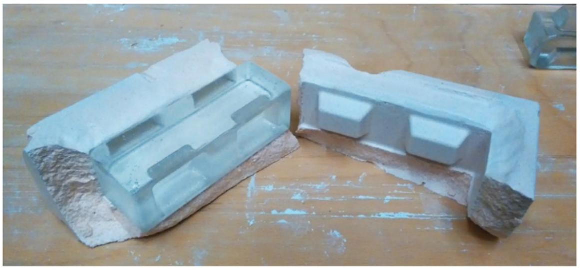

Fig. 5. Disposable mould.

thermal masses in the furnace, even the geometry and characteristics of the furnace itself. Hence, despite the existence of several guides in the scientific and industrial literature regarding the annealing cycle of cast objects, these are often tailored to specific circumstances and include unclear assumptions [15]. Due to the above reasons, even though the desired heat transfer can be calculated, in practice, the annealing schedule of large 3-dimensional cast units is often based on practical experience [12].

2.3. Mould types

Table 3 summarizes the characteristics of the prevailing mould types available for glass casting, illustrated in Fig. 4. The choice of mould mainly depends on the production volume and desired level of accuracy of the glass product, and is cost and time driven. Therefore, disposable moulds are more efficient for single component or small batch castings, as they are significantly cheaper than the permanent mould alternatives. For disposable moulds (Fig. 5), the level of achieved accuracy and maximum melting temperature can vary, from cheap investment silica-plaster moulds for castings below 1.000 °C to milled alumina-silica fiber ceramics of top performance. In both cases though, the glass surface in contact with the mould will acquire a translucent, rough skin that requires post-processing for a transparent result. Due to the brittle nature of these moulds, quenching is not recommended, thus their common application in kiln-casting.

For a series production, permanent moulds from steel or graphite (Fig. 6) are preferred in combination with the melt-quenching technique that is more time-efficient compared to kiln-casting. With such moulds, much higher accuracy can be obtained, especially in the case of pressed-moulds. A high level of surface detailing can also be achieved with the use of graphite moulds. To avoid further deviations, the mould should not be removed during the annealing stage, situation only possible with steel. The coating of the steel mould with a release agent –usually boron nitride or graphite- is therefore crucial for the easy release of the glass component. The permanent moulds can be adjustable as well (Fig. 7), to allow for shape flexibility; yet such choice compromises the level of accuracy. Overall the resulting surface is glossy and transparent and, in relation to the allowed tolerances, minimum or no post-processing is required - provided that the moulds have been properly preheated prior to casting. Inadequate preheating of the moulds increases the risk of surface chills at the glass, especially in the case of graphite moulds. Finally, although the complexity of the shape is not a significant cost-affecting factor for disposable moulds, it can sensibly increase the price of steel and graphite moulds. For complex projects that require numerous, different, yet accurately cast components, novel solutions need to be developed. A promising affordable mould solution for customized glass components of high accuracy can be found in the 3D-printed sand moulds developed by Arup and 3Dealise [16] for the casting of complex and individually produced steel nodes. Sand moulds are commonly used by glass artists as a cost-efficient solution for glass casting. This technique is not used to produce building elements and results in low accuracy. However, in the authors' opinion, the development of automated, customized 3D-printed sand moulds of high accuracy can revolutionize the way we design and produce cast glass elements.

3. Overview and assessment of large-scale non-architectural cast glass applications

3.1. The evolution of the telescope mirror blanks

Cast glass is the oldest method of glassmaking. Beads and other small objects, made of molten glass cast in moulds, date back to more than 2000 B.C in Mesopotamia [17]. In the Roman times, pyrotechnology was already so developed that allowed for the casting of monolithic glass blocks weighing several tons each. Such glass slabs were broken into smaller chunks and transported to secondary workshops to be fashioned into objects [18].

3.1.1. Reducing weight: The invention of the honeycomb structure

Nowadays, the largest monolithic pieces of cast glass are the mirrors of giant ground-based telescopes [19]. Spanning several meters these multi-ton parabolic-shaped mirrors typically employ a honeycomb structure to ensure the desired stiffness while significantly reducing their weight. Besides, a thinner blank with supportive ribs adjusts to temperature fluctuations more rapidly and anneals considerably faster [20]. The first mirror using a honeycomb geometry is the 5 m blank of the Hale telescope for the Mt. Palomar Observatory (Fig. 8), cast in 1936[3] by Corning using Pyrex® glass. A new glass blend at the time, Pyrex® would allow the mirror to expand and contract considerably less than regular glass, reducing distortion. The supporting ribs were formed by introducing silica firebrick (ceramic) cores in the mirror's steel mould. A special furnace was built to heat the glass to 1482 °C, so that it could successfully flow between the ribs [20].[4] The honeycomb mirror of 15 t in weight, had to remain approximately 10 months in an electrically heated annealer to be properly annealed [21,22]. The flat top surface of the mirror was ground afterwards to the desired parabolic shape in a process lasting more than a decade.

3.1.2. Reducing post-processing: Spin casting

The meticulous and time-consuming process of obtaining the desired concave shape by grinding had to be revised in the next decades. The 2.4 m in diameter mirror of the Hubble telescope for example, was realized in 1979 by fusing a thin faceplate, a back plate, rings and a honeycomb lattice core into a single unit out of Ultra Low Expansion (ULE®) glass (Fig. 9). Through slumping a concave front surface was created, reducing greatly the polishing needed.[5] Even so, 3 years of post-processing were required to achieve the desired precision.

In the 1980's a new method for making monolithic, parabolic-shaped telescope mirrors whilst minimizing post-processing was employed: Spin-casting [20].

By melting and annealing the glass into a spinning mould a parabolic shape can be directly obtained, saving several tons of glass and reducing considerably the annealing and post-processing time. Spin-casting is employed for the current manufacturing of the seven honeycomb blanks of the *Giant Magellan Telescope*. Spanning 8.4 m in

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[3] Until that time telescope mirrors were made as solid glass disks; the largest measuring 2.5 m in diameter and requiring a year of annealing (Zirker, 2005) [20].

[4] Here, the second attempt to cast the mirror is described. In the first unsuccessful attempt, the steel bolts that held the firebricks in place melted due to the intense heat of themolten glass, allowing the firebricks to float, ruining the disc (Caltech, 2017) [23].

[5] During the fusing process, the whole assembly was supported at its centre and the outer rim was allowed to slump, creating a convex backside and concave front. The same technology, called hex seal, was used to produce the 8.3 m blank of the *Subaru* Telescope and the 8.1 m blanks of the *Gemini 8-M* Telescopes.

Fig. 6. High precision open steel moulds used for the manufacturing of the glass blocks for the *Crystal Houses* project.

Fig. 7. Adjustable graphite mould at *John Lewis Glass Studio* for the components of the *Ice Falls* project by James Carpenter.

diameter each, these mirrors are the largest contemporary monolithic cast glass pieces. To allow for the constant rotation of the glass during both its melting and annealing, the mirrors are kiln-cast in a rotating furnace. In specific, a disposable mould out of silica-alumina fiber core boxes with a hexagonal cross-section, is built within a rotating kiln (Fig. 10). Silica-alumina fiber can withstand both the heat and the pressure of the casting process, yet it can crumble easily with water pressure after the mirror is annealed. The mirrors are fabricated using E6 borosilicate glass by *Ohara*. Compared to Pyrex®, E6 glass expands and contracts considerably less, melts and flows easily at reasonably low temperatures and is of competitive price [20]. Approximately 20 t of presorted glass chunks are laid on the top of the cores, then the furnace is sealed and the temperature slowly rises to 1180 °C. As the glass liquefies the kiln rotates at a constant speed of 6.8 rpm. While spinning, the mirror takes the desired concave shape to an accuracy of 0.25 mm, then finally solidifies through a 3 month annealing process - considerably faster compared to the previously analyzed examples. The cast blank requires three years to acquire its final shape- same timeframe needed for the four times smaller Hubble mirror.

3.2. Other applications

3.2.1. Lead glass blocks

Apart from the mirror blanks, some of the largest contemporary monolithic cast glass pieces are made for radiation-shields. These glass pieces, measuring up to 1.4 × 1.4 × 0.4 m and weighing about 4.5 t are made of glass with a high content of lead (PbO). With PbO ranging between 33% and 70%, these blocks have an increased density, between 3220 and 5180 kg/m^3 [24]. The casting process followed by Corning at the Fontainebleau Factory for the production of such blocks is as follows: A pre-heated open steel mould, coated with refractory paper liner, is set on a moving table inside a thermally controlled kiln. The glass is delivered by gravity from a tube in a continuous stream. To avoid the creation of cords, the table moves down at constant speed calculated from the

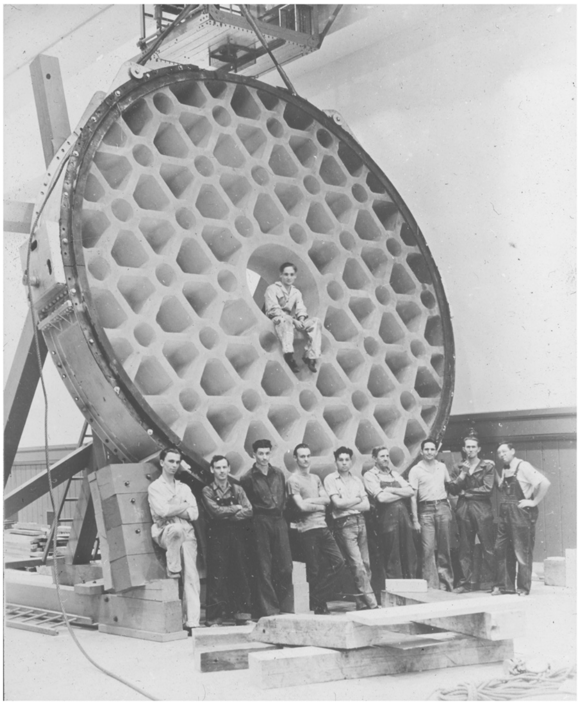

Fig. 8. The 5 m glass mirror of the Mt. Palomar telescope. Image credits: Collection of the *Rakow Research Library*, *The Corning Museum of Glass* (Number: 1000093965).

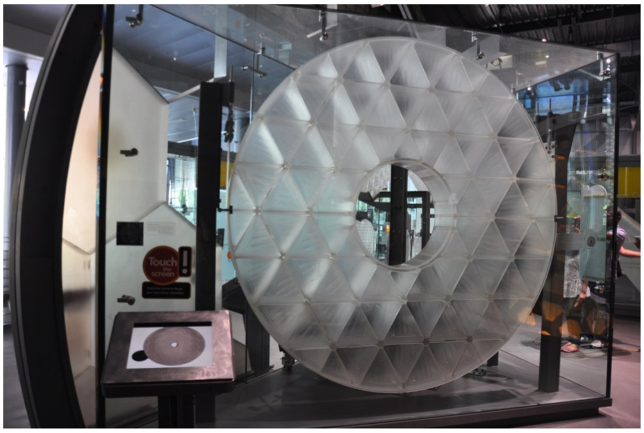

Fig. 9. Fused-silica prototype of the Hubble mirror at the *Corning Museum of Glass*.

glass flow and mould dimensions. When the target glass thickness is reached the mould is transferred from the kiln into a static furnace for annealing. The glass surface is still convex as viscosity impedes a perfect fill at the mould corners. The block is therefore re-heated marginally over the softening point to reduce viscosity and allow for optimal filling. Once ready the annealing cycle starts to cool the block gradually to room temperature within the mould. A block of 64% PbO lead glass and 300 mm thickness requires approximately 1 month of annealing, whereas a 400 mm thick block requires 2 months respectively [25].

3.2.2. Glass sculptures

Art is another field employing big cast blocks exhibiting the variety of shapes we can achieve through glass casting. Numerous glass artists, such as *Karen Le Monte*, *Roni Horn* and *David Ruth* (Figs. 11 and 12), have worked with considerably sized cast glass components. Perhaps the largest monolithic cast glass sculpture is the "*Pink Tons*" by *Roni Horn*. The 4.5 t solid cube presents internal cracks, probably generated due to improper annealing. Nonetheless, little information can be found regarding the annealing schedule and process of such art pieces.

A challenging and well-documented example of cast glass art is the block for the *Denis Altar* in France, cast as well in Corning's facilities at Fontainebleau. The 1.42 × 1.42 × 0.28 m block is made with Corning 7056 optical glass and weighs approximately 1.4 t. The block had to perfectly fit to the profile of the supporting stone (Fig. 13), requiring a high bottom

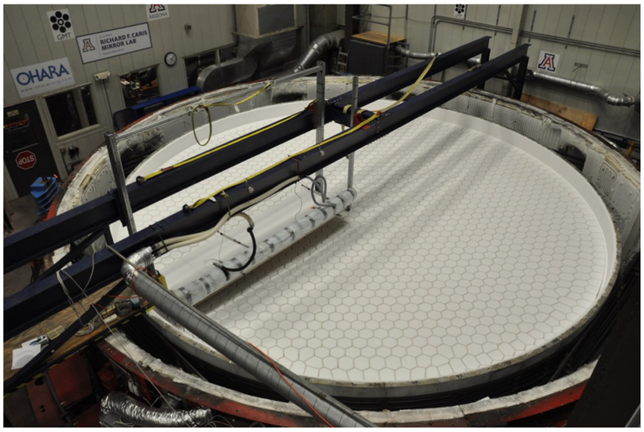

Fig. 10. Disposable mould for the *Giant Magellan* blanks built within the bottom part of the rotating kiln at the *Steward Observatory in Arizona*.

Fig. 11. Solid glass sculptures by *Roni Horn*.

Fig. 12. A human-scale cast piece by *Karen le Monte* at the *Corning Museum of Glass*.

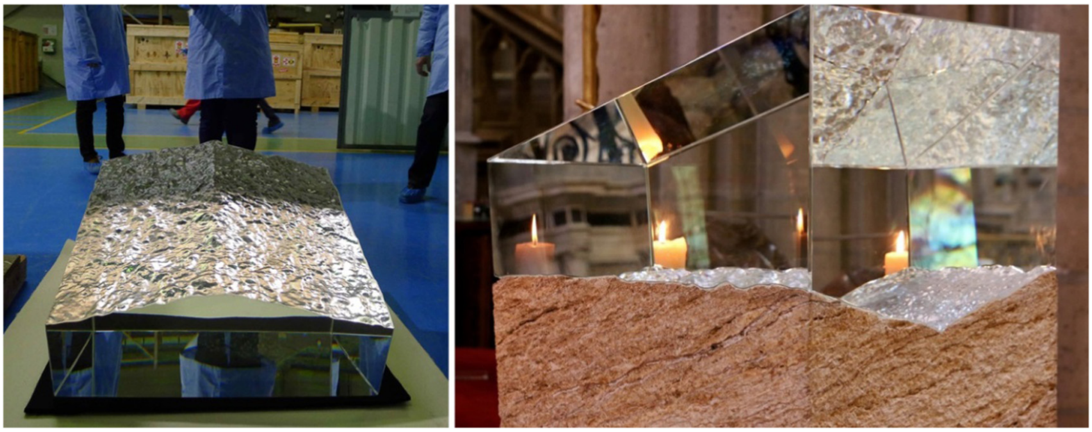

Fig. 13. The 1.4 t cast component of the *Denis Altar*. Image credits: Thierry Dannoux.

Table 4
Dimensions and characteristics of some of the largest cast glass components made. Data for the telescope mirrors as provided by [20,26].

Application	Unit	Hale Telescope Mirror	Giant Magellan Telescope mirror	Nuclear Glass Blocks	Dennis Altar glass slab
Dimensions	[mm]	Ø 5080	Ø 8417	1400 × 1600	1420 × 1420
Thickness	[mm]	660 (when cast)	Max:894 Min:437	400	280
Geometry		Honeycomb disc	Honeycomb disc	Rectangular massive block	Rectangular massive block
Glass type		Pyrex$^{®}$	E6 borosilicate glass	Corning$^{®}$RSG52 (70 PbO%)	Corning$^{®}$7506 (alkali-borosiicate)
Density	[g/cm^3]	2.23	2.18	5.22	2.29
Component weight	[t]	20 (14.5 after polishing)	16	4.5	1.4
$T_{batch\ melt}$	C°	1482	1180	1500	1495
Exp. Coeff.	1/°C	32.5×10^{-7}	28×10^{-7}	82.8×10^{-7}	51.5×10^{-7}
Mould type		Steel mould with silica firebrick cores bolted with steel bolts	Base: SIC baselites lined with aluminosilicate refractory fiberboard Cores: Carborundum Carbofrax SiC	Adjustable steel mould with refractory paper liner	Steel mould with refractory paper liner
Casting method		Hot-pouring Annealing within mould	Spin-(kiln) Casting Annealing within mould	Hot-pouring within kiln Annealing within mould	Hot-pouring Reheating above softening point to imprint pattern
Anneal. time	Months	~ 10	~ 3	~ 2	~ 1 (total production time 3 months)
Post-processing		Grinding and polishing (10 years)	Grinding and polishing (3 years)	Slicing to size and polishing	Polishing

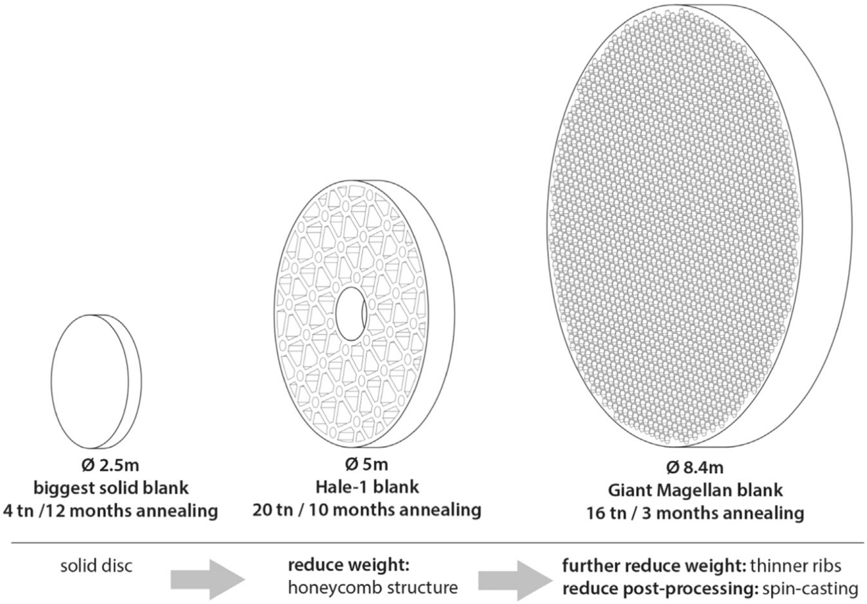

Fig. 14. Evolution of the cast mirror blanks in size due to smart geometry and manufacturing process.

Fig. 15. Segment of the Giant Magellan's blank at the Steward Observatory, Arizona.

surface accuracy. To achieve this, the glass block was initially cast rectangular with all sides flat in a large metal container, coated with non-stick refractory paper. The piece required roughly one month of annealing. Then the stone surface was imprinted on the glass: A plaster mould with the desired pattern loaded by 500 kg was set at room temperature on the glass. The assembly was slowly reheated to its softening point (690 °C) and kept at that temperature for a month for the pattern to be imprinted. The block was then slowly cooled down to room temperature within another month.

3.3. Observations

Table 4 summarizes the characteristics of the above discussed examples. Cast glass objects of such scale give us insight into both the potential and the practical limitations of glass casting. The larger the component, the exponentially longer the annealing time. An annealing time of several months may be acceptable for astronomical research, yet it would render a cast glass component financially unjustifiable for architectural and structural applications.

Hence, the choice of glass, casting method and overall geometry greatly influences the annealing time and safeguards the component's marketability. For example, compared to the Hale and Hubble blanks, the Giant Magellan Telescope mirrors present significantly larger overall dimensions (Fig. 14); nonetheless, the substantially lighter structure (Table 4, Fig. 15) and the choice of glass considerably reduce their total annealing time.

Such smart geometry could also be implemented in cast components for architectural, load-bearing purposes. For example, compared to solid ones, glass blocks following the honeycomb principle would be sufficiently rigid, but faster to produce and lightweight, facilitating transportation and handling.

The casting method can also reduce the required post-processing, decreasing the manufacturing costs and production time as well.

As for unique, more elaborate or variable components, singular disposable moulds are preferable over reusable adjustable ones.

The presented examples also illustrate the importance of a homogeneous mass distribution to avoid uneven cooling. The above case-studies also highlight the influence of the critical dimension, namely the thickness, to the total annealing time: i.e. an increase of 100 mm in the thickness of the massive lead blocks doubles the annealing time.

Lastly, art applications indicate the possibilities of further shaping a component through a specific heating treatment. These include the creation of the desired finished surface but also the minimization of the capillary effect at the components' edges. Nevertheless, such a process would significantly delay the overall production.

In summary, there are many factors influencing the total annealing time of a cast glass component; geometry being the most decisive. If these parameters are controlled from the design stage, structural and efficient cast glass components can be made of various shapes and forms.

4. Applicability of solid glass blocks in structural, architectural examples: current structural systems

In respect to the meticulous and lengthy cooling process, in architectural applications, solid cast glass components have been commercialized up to the size range of standard masonry bricks. Owing to their large cross-sectional area, solid glass bricks are promising structural components[6] that can fully exploit glass's compressive strength. By forming repetitive components, self-supporting, three-dimensional all-glass structures of undisturbed transparency can be achieved. At present the non-standardized, virtually manual, manufacturing process of solid glass blocks and the lack of substantial research on their assembly and structural performance have limited their structural application in only a few built architectural examples.[7] The most characteristic case studies are the envelopes of the *Atocha Memorial* [27], the *Crown Fountain* [28], the *Optical House* [29] and the *Crystal Houses* [12] (Fig. 16). Table 5 contains a summary of each project's characteristics. To ensure the desired stability and stiffness of the glass assembly, such envelopes currently employ either a supportive substructure or a rigid structural adhesive (Fig. 17). A promising third structural concept, comprising interlocking cast components has been recently introduced by [30] but is yet to be realized in construction.

4.1. Solid glass block envelopes with supportive substructure

In this system, a supportive, metal substructure carries the tensile forces and ensures the desired stiffness and buckling resistance, allowing the glass assembly to perform mainly under compression. The most characteristic realized examples using this principle are the *Crown Fountain* and the *Optical House*. In specific, the 8.6 × 8.6 m envelope of the *Optical House* (Fig. 18) consists of 6000 solid blocks, which are punctured and threaded from below (Fig. 19) in a pre-tensioned vertical mesh of 75 stainless steel rods suspended from a steel beam (Fig. 20) encased in reinforced concrete [29]. The mesh withstands the lateral forces, whereas glass carries its own weight. Two vertical steel fins further serve against wind loads. In this way, a façade of high slenderness is attained. The rods are connected with stainless steel flat bars (40 mm × 4 mm) that seat within the 50 mm thick glass blocks at 100 mm intervals, to reduce lateral stresses directed to the glass blocks (Figs. 20 and 21). The resulting structure is mortar-free [29]. Borosilicate glass was opted for the glass blocks, due to its increased optical qualities compared to soda-lime [33].

The *Crown Fountain* (Fig. 22) employs a different system, a combination of pre-assembled glass block grates connected to a stainless steel internal frame, which carries both vertical and lateral forces [28]. Each of the two towers of 12.5 m × 7 m × 4.9 m employs a total of 11.250 cast glass blocks, pre-assembled in grates of approx. 250 units, stacked and welded together. All forces are transferred by an embedded steel T-profile frame to the base via a zigzag pattern. The lateral stability of the tower is enhanced by Ø13 mm rods anchored to the structure and triangular corner brackets. The blocks were made using melt-quenching and an open, high-precision steel mould. This resulted to blocks that needed to be polished only on one side. Approximately 350 blocks were produced per day over a period of 4 months.

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[6] In comparison, standardized hollow glass blocks are considered non-load-bearing (Watts, 2014) [31] due to their reduced wall thickness that results in stress concentrations that in turn lead to early failure.

[7] Structures employing hollow glass blocks or solid glass blocks that are non-load-bearing are out of the scope of this research. Cast glass has already been applied in several architectural projects as façade cladding. Some of the most inspiring projects are the *Ice Falls* and the *Periscope Window* by [32].

Fig. 16. Characteristic examples of structures employing cast glass blocks: The *Atocha Memorial* (left) *Crystal Houses* (centre), and the *Crown Fountain* (right).

Table 5
Overview of the characteristics of realized self-supporting envelopes using solid cast glass components.

Project	**Optical house**	**Crown fountain**	**Atocha memorial**	**Crystal house**
Location	Hiroshima Japan	Chicago Illinois, USA	Madrid Spain	Amsterdam The Netherlands
Envelope dimensions [m]	8.6 × 8.6	12.5 × 7 × 4.9	8 × 11	10 × 12
Geometry	Flat envelope	Cube	Elliptical cylinder	Flat envelope
Structural system	Supportive substructure	Supportive substructure	Adhesively bonded	Adhesively bonded
Number of blocks	6000	22,500	15,600	7500
Size of blocks [mm]	235 × 50 × 50	127 × 254 × 51	300 × 200 × 70	210 × 210 × 65 210 × 157.5 × 65 210 × 105 × 65
Number of different blocks	1	1	1	3
Weight of block [kg]	2.2	4.5	8.4	7.2/5.4/3.6
Total weight [t]	13	50.6	130	40.5
Type of glass	Borosilicate	Low-iron soda-lime	Borosilicate	Low-iron soda-lime
Annealing time	unknown	unknown	20 h	8–38 h (size dependent)
Type of mould	Press steel mould	Open steel mould	Press steel mould	Open steel mould
Post-processing	no	Polishing in one side	no	Polishing 2 faces to ± 0.25 mm precision

4.2. Adhesively bonded blocks

An entirely transparent cast glass structure can be built by bonding the glass blocks together with a colourless rigid structural adhesive. In this way material-compatible, low-stress and permanently resistant connections are established. In such a system, the mechanical properties of the adhesive are equally critical to the ones of the glass blocks; it is their interaction as one structural unit that defines the system's structural behaviour. The most favourable structural performance is when adhesive and glass fully cooperate and the assembly behaves as a single rigid unit under loading, resulting in a homogeneous load distribution [12]. Thus, rigid adhesives, such as acrylates and epoxies are necessary to ensure the desired bond strength. Two good examples of adhesively bonded glass envelopes from cast glass components are the *Atocha Memorial* and the *Crystal Houses*.

The *Atocha Memorial* (Fig. 23), approximately elliptical in plan and 11 m high, is built from 15,600 glass borosilicate blocks bonded together with a 2 mm thick transparent UV-curing adhesive [27]. To obtain the cylindrical shape of the monument (Fig. 24) by a single block geometry, a customized cast glass component was designed, convex on one side and concave on the other (Fig. 25). The curvature turns the glass wall into a shell structure of increased stiffness, sparing the necessity of a substructure. The glass roof is connected to the glass block structure in a rigid way to constrain the upper free edge and prevent the ovalisation of the section [34].

The glass elements experience high temperature fluctuations in Madrid, resulting in high surface tensions. Therefore, owing to its comparably lower thermal expansion coefficient than soda-lime, borosilicate glass was opted for the fabrication of the blocks. By casting borosilicate glass in high precision press steel moulds, the required ± 1 mm tolerance was met, guarantying the applicability and uniformity of the selected adhesive without the need of post-processing [34]. The annealing time for each brick was 20 h.

The special characteristics of the adhesive required the construction of the envelope inside a UV-filtering tent for protection against solar radiation, dust and adverse weather conditions (Fig. 26). Both temperature and humidity levels were controlled. Prior to construction, various tests were performed to validate the structural performance of the adhesive-glass assembly. According to the calculations, almost the entire contact area of the blocks had to be bonded. At the same time

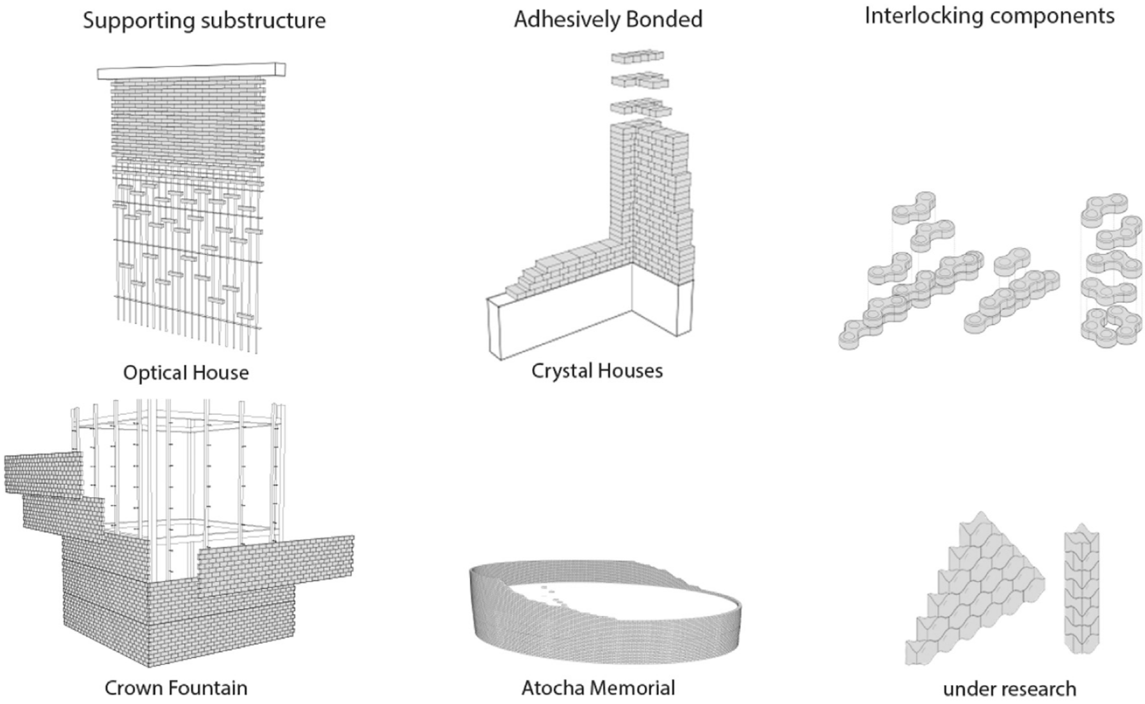


Fig. 17. Illustration of the structural systems currently developed for structures using cast glass components.

Fig. 18. The *Optical House*. Image credits: Koji Fujii/Nacasa & Partners Inc.

overflow had to be minimized. A special bonding method was developed, to distribute the adhesive in the right amount and prevent the generation of air bubbles.

Logistics of the project were also challenging. Two 10 h shifts were established with 11 specialized workers per shift, six days per week, for the cleaning, bonding by UV-curing and external sealing of the blocks one by one, resulting to 500–600 glued blocks per day [34].

Crystal Houses is another great example of an adhesively bonded, highly transparent glass bock envelope, made as an accurate yet completely transparent reproduction of the previous, 19th century masonry brick façade [4]. Based on the brick modules of the original façade, the 10 × 12 m transparent elevation employs more than 6500 solid glass bricks, of three different sizes (Table 5), reinterpreting the traditional brickwork; while massive cast glass elements reproduce the classic timber door and window frames. Towards the top, terracotta bricks intermingle with glass ones, gradually transforming the glass elevation to a traditional brick façade (Figs. 27 and 28). The architects' desire for unimpeded transparency, rendered as sole solution the creation of an entirely self-supporting adhesively-bonded glass brick system [35].

Extended research and testing of various adhesive types by [35] led

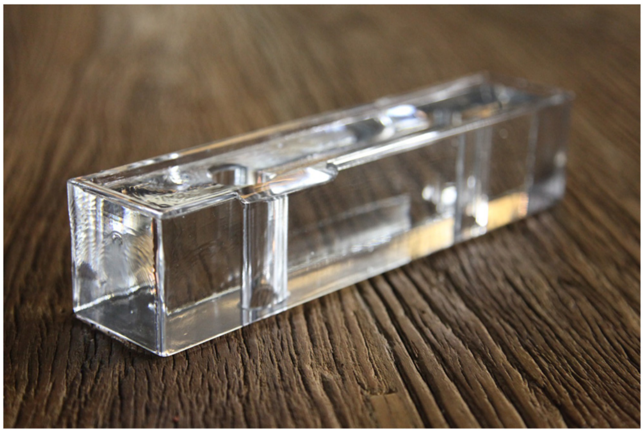


Fig. 19. Glass block unit of the *Optical House*. Image credits: Hiroshi Nakamura & NAP.

Fig. 20. Assembly of the *Optical House*. Image credits: Hirsohi Nakamura & NAP.

to the eventual selection of *Delo Photobond 4468;* a colourless, UV-curing, one-component acrylate, designed for high strength bonding between glass components.

Structural experiments indicated the application thickness for an optimum bond strength to be between 0.2 and 0.3 mm. In addition, the construction of four architectural wall mock-ups by [35] with tolerances ranging from ± 0.25 mm to ± 0.5 mm in the height and flatness of the bricks indicated that tolerances above ± 0.25 mm result to an uneven spread of the adhesive that can greatly affect the structural performance. Moreover, the visual result of the transparent wall is disturbed due to induced air gaps in the adhesive layer. The relatively low viscosity of the specific glue allowed a homogeneous bonding only at the horizontal surfaces of the glass bricks; the vertical joints, approx. 1 mm in width, were left open, allowing as well for thermal expansion. Accordingly, it was determined that the glass blocks' top and bottom surfaces should be flat within ± 0.25 mm (Figs. 29 and 30) [35].

The thickness of each construction layer had to be confined within the same dimensional accuracy, as any accumulated deviation larger than the required bonding thickness could lead to uneven and improper bonding. The demand for this remarkably high level of accuracy and transparency, introduced various challenges in the engineering and construction of the façade. The required ± 0.25 mm tolerance influenced the selection of glass recipe and mould as well. Soda-lime glass and open high precision moulds were chosen to prevent an unnecessary increase in production costs as the high required accuracy would necessitate the mechanical post-processing of the block's bonding surfaces anyway [12]. Depending on the block's size the annealing time ranged between 8 h and 38 h. The 65 mm thickness of the blocks hindered an accurate stress measurement by a *Scattered Light Polariscope* stress-meter; instead a qualitative analysis of strain concentration was made using cross polarization (Fig. 31).

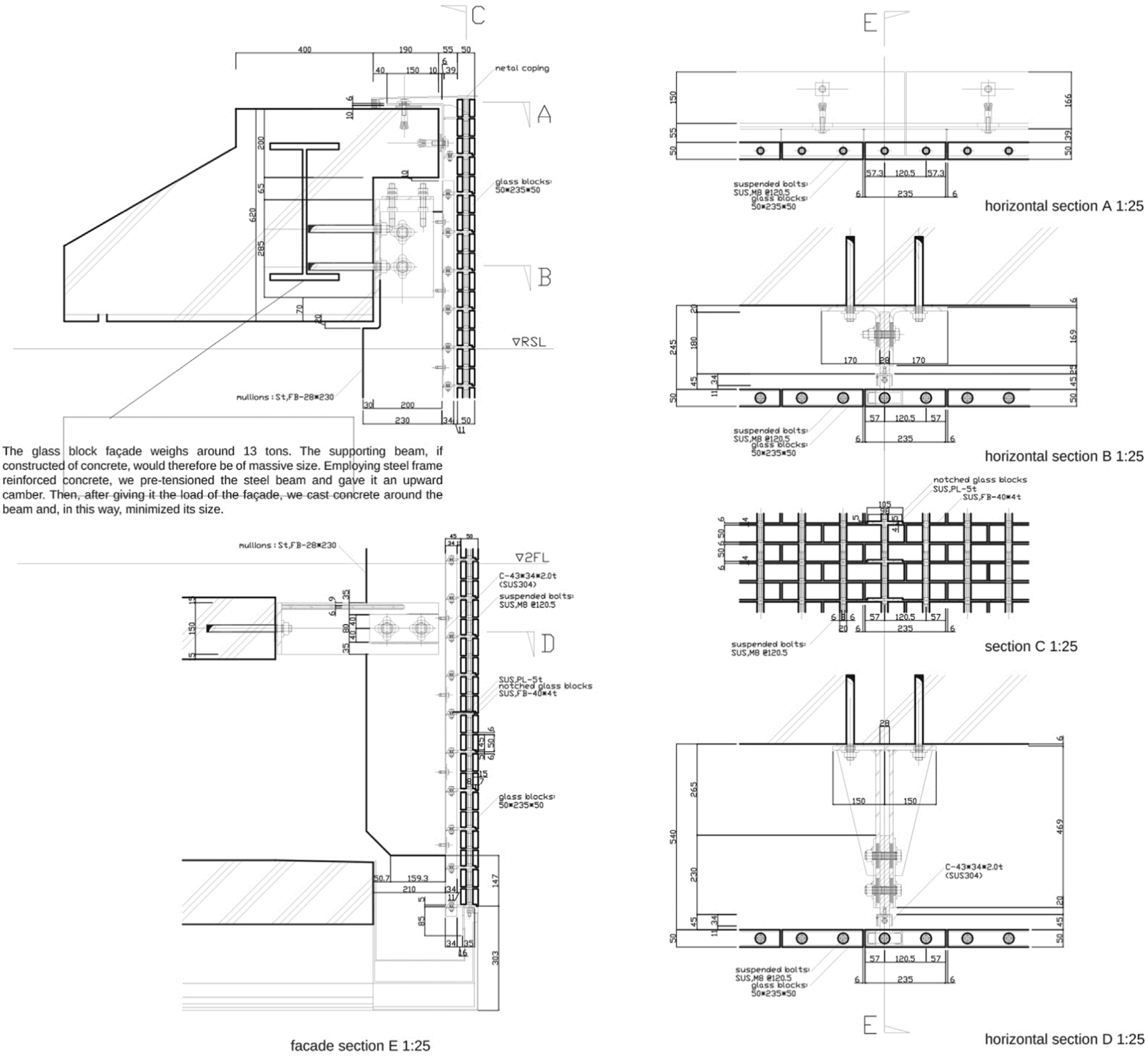
Eventually the horizontal, bonding surfaces of the blocks were CNC polished to meet the desired precision. Structural tests and architectural mock-ups by [35] suggested the bonding of the complete contact surface between blocks. Through the uniform application of the adhesive both a homogeneous load distribution and maximized transparency are attained. To eliminate defects in the adhesive layer that would deeply affect the final visual result, a customized bonding method was developed, using custom-designed self-reinforced polypropylene forms for controlling the flow, spread and amount of the adhesive (Fig. 32).

Oikonomopoulou et al., (2017) [12] discusses the complex logistics of the project, which are similar to the *Atocha Memorial* project. Nonetheless, the 8 times less allowable thickness of the adhesive, introduced a higher complexity level of the manual bonding process that called for a highly skilled crew and a strictly controlled construction. A 12 h working schedule was established, 5 days per week. 7–9 highly skilled workers bonded and sealed on average 80–100 blocks per day under the supervision of 2 quality control engineers and the construction site supervisor. The entire built up of the façade took 7 months.

4.3. Interlocking components

This third, new concept – still in a research stage– explores the potential of full-glass compressive structures, such as columns, walls and arches, from interlocking cast glass components. In this case, the overall stability is achieved through compression provided by the construction's self-weight combined with the interlocking geometry that restrains lateral movements, resulting to a structure with minimal, if any, metal framing. Furthermore, the suggested system proposes the use of a dry, colourless interlayer, such as polyurethane rubber (PU) or Polyvinyl Chloride (PVC), as an intermediate medium between the glass units (Fig. 33).

This allows for a demountable structure that enables the circular use of the glass components: they can be retrieved intact and reused or, eventually, recycled as they are not contaminated by foreign substances such as coatings or adhesives. Moreover, the dry interlayer prevents stress concentrations due to glass-to-glass contact and compensates for the inevitable dimensional tolerances in the cast units' size [30]. So far, various geometries, dry interlayers and structural applications have been explored and experimentally tested. In particular, [36,37,38] studied a dry-assembled arched glass masonry bridge interlocking in one direction (Fig. 34). All other research projects focus on systems that confine the movement in both axial and transverse direction. Akerboom (2016) [39] studied the realization of a glass column out of solid and hollow interlocking cast components. The column's cross-section was optimized based on its structural capacity and performance. Barou



The glass block façade weighs around 13 tons. The supporting beam, if constructed of concrete, would therefore be of massive size. Employing steel frame reinforced concrete, we pre-tensioned the steel beam and gave it an upward camber. Then, after giving it the load of the façade, we cast concrete around the beam and, in this way, minimized its size.

Fig. 21. Detail drawings of the *Optical House's* glass block system. Drawing courtesy: Hiroshi Nakamura & NAP.

et al., (2016) [40] proposed an interlocking system for flat, self-supporting envelopes using a brick inspired by the LEGO® block (Fig. 35, left). Frigo (2017) [30,41,42] further developed the concept, suggesting more curved geometries and an equal mass distribution, in respect to the manufacturing process of cast glass and towards an increased shear capacity (Table 6). Numerical modeling of the osteomorphic block (Fig. 35, centre, right) by [42] indicated that a decrease in the blocks' height reduces its shear capacity and can alter the system's failure mechanism. A lower brick is more susceptible to bending, whereas for a higher brick the shear lock failure is proven to be more critical.

Although there are limited experimental tests for deriving statistical data, they suggest that interlocking cast glass components can be a promising solution for future structural applications. An important input from this research is the development of units featuring more organic shapes and curved geometries (Figs. 36 and 37), avoiding sharp edges to prevent residual stress concentrations, fitting the characteristics and peculiarities of cast glass as a construction material [30].

4.4. Observations

The comparative charts in Tables 5 and 7 lead to general conclusions regarding the applicability of cast glass in load-bearing architecture. Due to the lack of sufficient and comparable technical data, the thermal and acoustic performance of the presented solid cast glass applications[8] have been excluded from this paper.

All realized projects have been made using primary casting, and employed usually a singular block geometry of a simple form and less than 10 kg in weight. Either borosilicate or soda-lime glass are employed, depending on the project's location and the required

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[8] In general, solid glass blocks exhibit a reduced thermal and acoustic resistance compared to hollow glass blocks. The latter, due to the air cavity, exhibit an increased thermal resistance and can reduce sound transmission. On the other hand, due to the aforementioned air cavity, hollow glass-blocks are considered non-load-bearing and cannot be applied in structural applications such as the ones analyzed in this paper.

Fig. 22. One of the *Crown Fountain* towers.

Fig. 23. The *Atocha Memorial*. Image credits: Bellapart, SAU.

dimensional accuracy.

Although primary casting requires higher working temperatures, it is considered a more cost-effective method for the production of numerous identical units.

Also, as described in chapter 2, the glass type, overall dimensions, form and volume of the object are key-factors for the total annealing time. Thus, smaller-sized and simple-shaped objects are preferred. For example, the solid glass bricks of 3.6 kg weight used in the *Crystal Houses* façade required 8 h of annealing, whereas components of double the volume (and critical dimension) and 7.2 kg weight, required an annealing cycle of 36–38 h respectively [12]. The annealing time can be further reduced if borosilicate glass is employed instead of soda-lime due to its improved thermal expansion coefficient (Table 2). A comparison between the 8.4 kg block of the *Atocha Memorial* and the 7.2 kg block of the *Crystal Houses* demonstrates this clearly. The former, although larger in dimensions and weight, required almost half the annealing time than the latter.

A limited mass, also facilitates the installation and handling processes. Moreover, a repetitive component geometry is essential for simplifying the production and assembly and for limiting the manufacturing costs, owing to a limited amount of moulds and a standardized production process.

Regarding the overall shape, little exploration has been made on the forms that can be achieved by cast glass in the realized projects

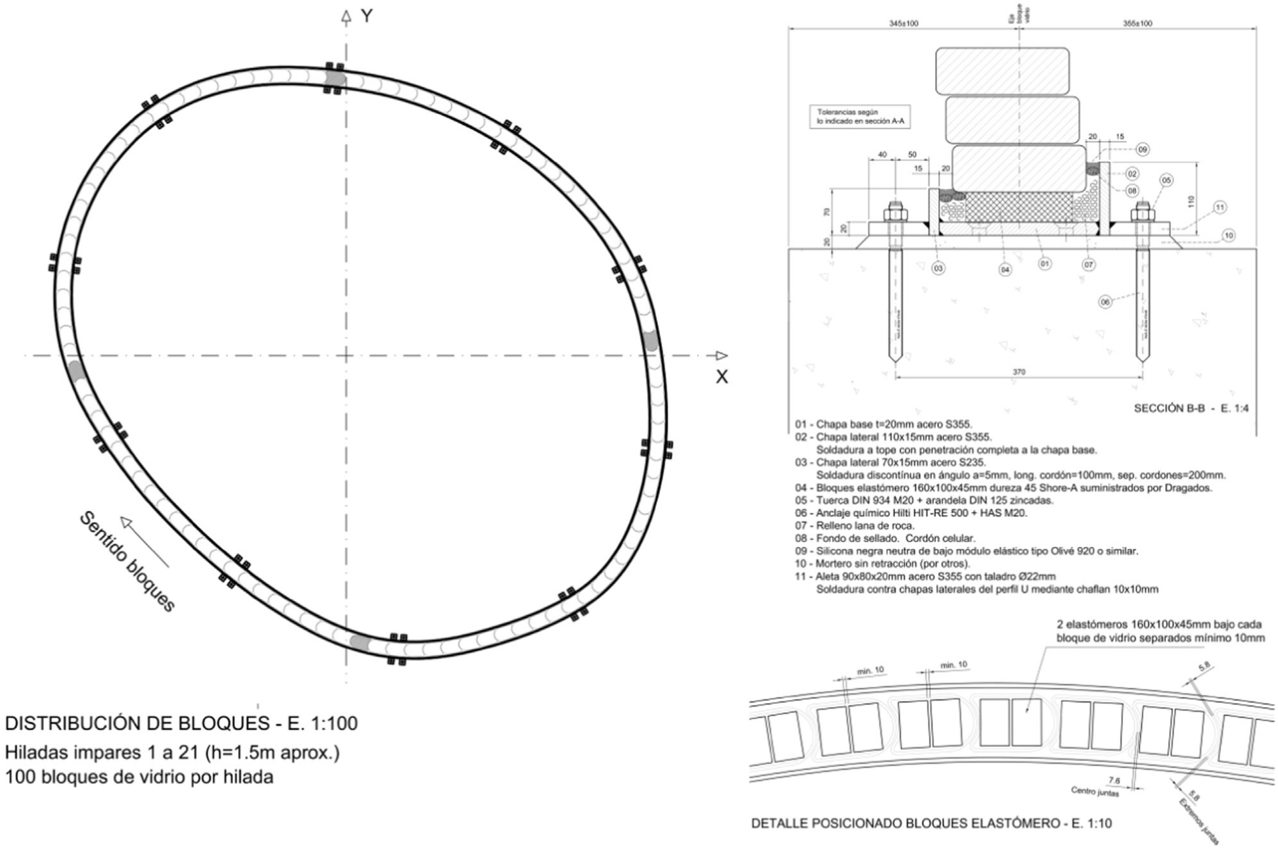


Fig. 24. Plan and details of the *Atocha Memorial* glass structure. Image credits: Bellapart.

Fig. 25. Glass block unit of the *Atocha Memorial*.

(Fig. 38). Research conducted so far in interlocking components shows a greater interest in developing shapes that match the properties of glass.

There are currently three developed structural systems for making self-supporting cast glass structures, employing: (1) a supportive substructure, (2) a stiff, colourless adhesive and (3) an interlocking geometry and a dry interlayer.

Whereas the first solution compromises the overall level of transparency and the second solution results to an irreversible, non-recyclable and challenging construction of intensive and meticulous labour, the topologically interlocking cast glass components can tackle the limitations imposed by both previous systems. Nonetheless, this solution has yet to be validated in practice.

Lastly, a crucial aspect that can greatly influence the performance of

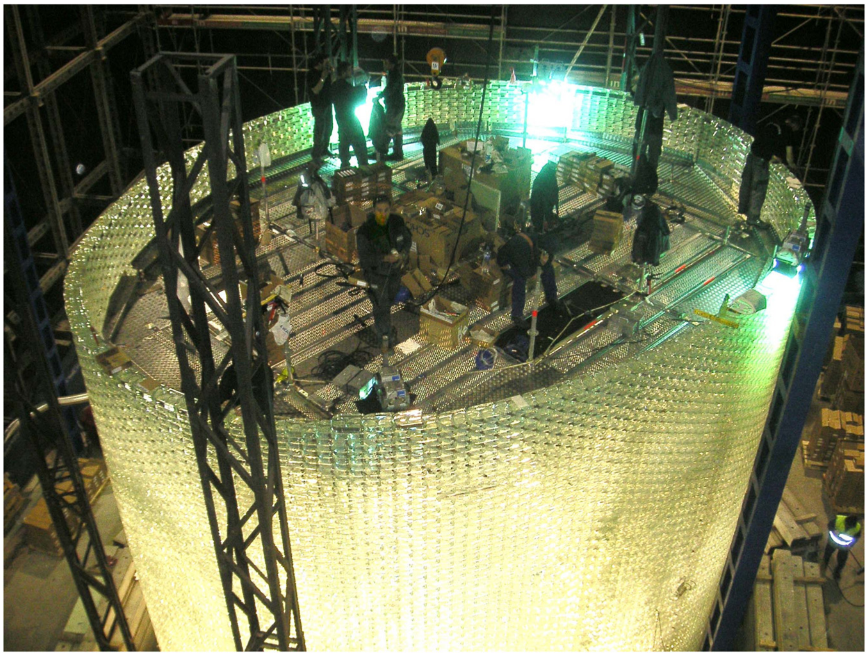


Fig. 26. Construction of the *Atocha Memorial*. Image credits: Bellapart, SAU.

Fig. 27. *Crystal Houses*, Site elevation. Image credits: MVRDV architects.

the structure is its overall geometry. Flat geometries or walls of high-slenderness have limited resistance to lateral loads and buckling and call for more challenging solutions than geometries with inherent stability such as closed shapes.

5. Discussion and conclusions

Overall, the analyzed examples suggest that at present, the cast glass components for structural purposes in architecture are crafted, rather than manufactured, to meet each project's demands. To the knowledge of the authors, none of the presented architectural projects has disclosed information regarding the price of the individual elements, as well as of the entire construction. It is anticipated that the custom-made and, to a certain extent, manual fabrication of the cast units and the lack of a standardized construction method, result in high manufacturing costs compared to conventional glass envelopes. As a result, cast glass has been confined to just a few load-bearing applications in architecture. Nonetheless, it is expected that an increased demand,

Fig. 28. Left: 3D visualization of the façade by MVRDV Architects. Right: The realized façade.

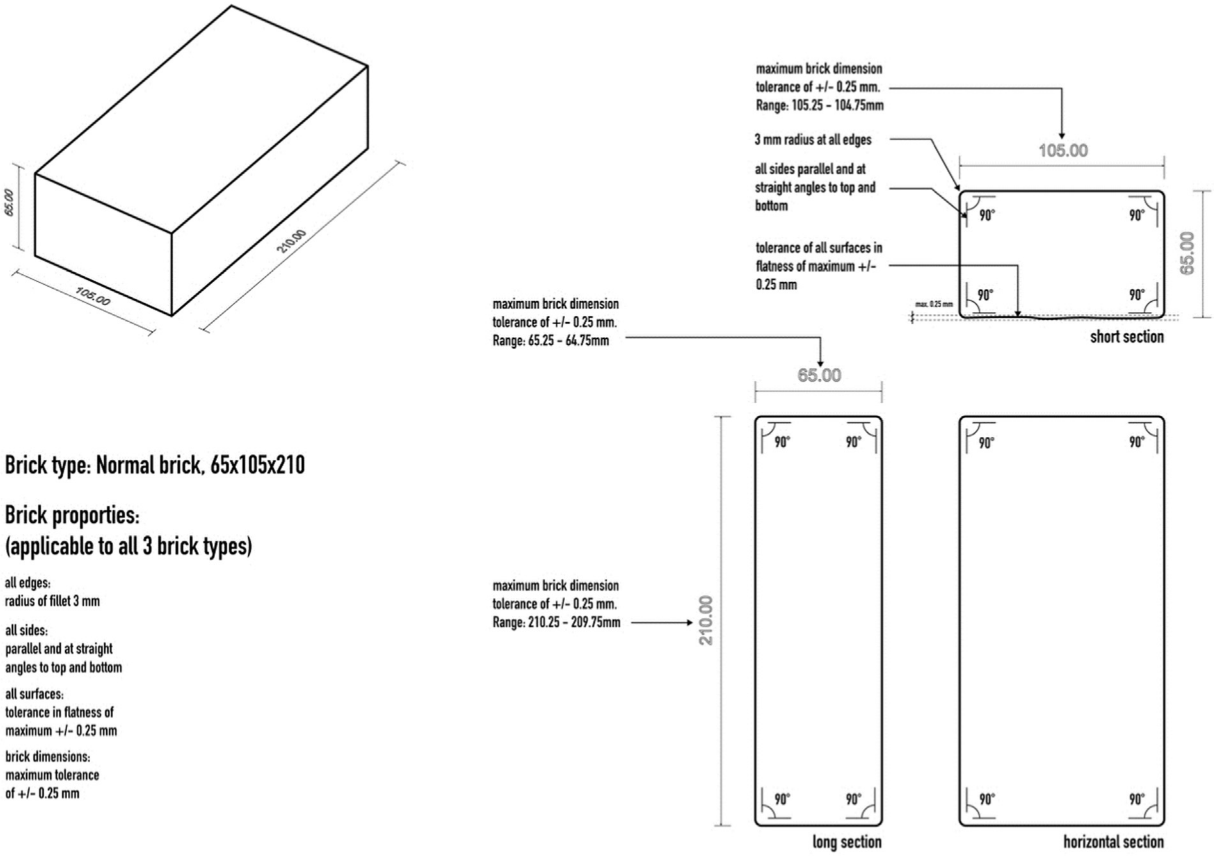


Fig. 29. Diagram indicating the properties and dimensional accuracy of a standard glass brick for the *Crystal Houses* façade project. Image credits: MVRDV Architects.

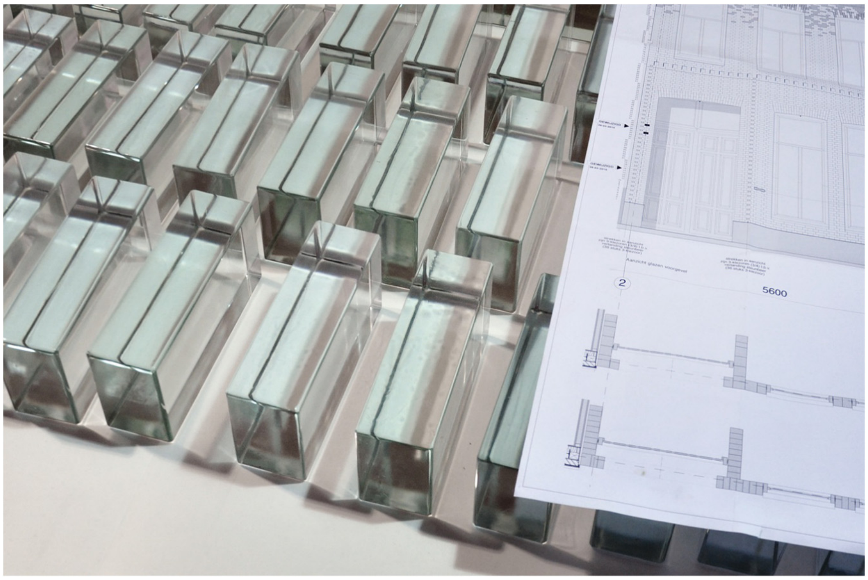


Fig. 30. Solid glass blocks used for the construction of the *Crystal Houses*.

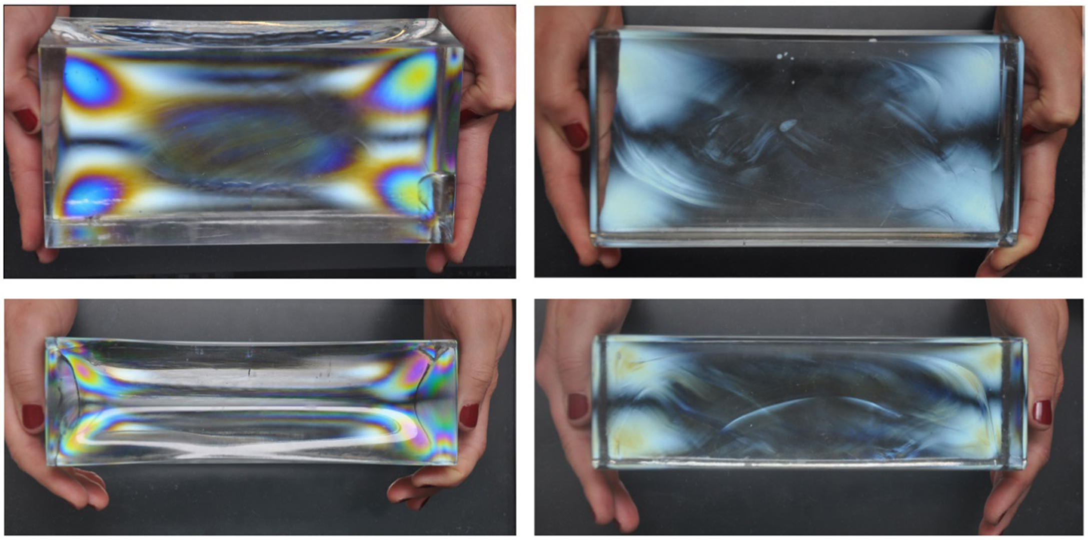


Fig. 31. Qualitative stress analysis through cross polarization. Bricks with clear indication of stresses (left) were discarded. Specimens with no visible strain concentration (right) were employed in the façade.

sufficient for a standardized production method, can greatly reduce the manufacturing cost of cast glass components. Indeed, cast glass casting exhibits great potential for creating diaphanous structural components of the desired shape and cross-section that can circumvent the geometrical limitations imposed by the virtually two-dimensional float glass. Solid, transparent glass columns, such as the one described by [39] and glass arches, such as the one by [36] are great relevant examples.

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 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 and components close to elliptical or rounded shapes are closer to this principle. The form of cast glass

Fig. 32. Bonding and curing of the adhesive at the *Crystal Houses*.

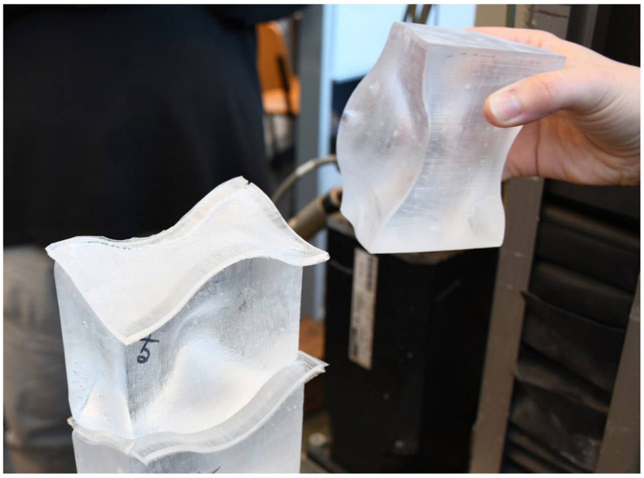


Fig. 33. Prototype of a 3 mm thick, cast interlayer from PU70 [30].

components can be further improved towards 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. Following the principle of the steel node described in [43], which was cast using a 3D-printed sand mould, innovative structural glass components can be made in a cost-efficient way (Fig. 39).

Geometry can also be exploited for creating sustainable cast glass components. Accordingly, interlocking components are promising building elements for demountable, circular constructions. Components can be also developed to improve the structure's thermal performance – i.e. by concentrating power through the development of a solid cast glass lens block for storage of solar energy (Fig. 39).

However, the real revolution in cast glass structures will be when a cost-efficient 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. Yet, production time can be reduced by optimizing the mass of the components. Mould costs are limiting the number of different components to just one. Adjustable steel moulds, can enable the production of components of different sizes by one mould. Moreover, 3D printed sand moulds can be a solution for making cost-efficient moulds for free-form cast glass components. Post-processing plays a significant financial factor and must be restricted; 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. Reheating the component to manipulate its surface is another process. Borosilicate glass can also be employed to achieve higher manufacturing accuracy due to its reduced thermal expansion. Although fused silica and 96% silica have an almost zero expansion, they involve a costly production

Fig. 34. Visualization (top) and a tested glass block prototype (bottom) of the dry-stacked glass arch bridge developed by [36].

Fig. 35. Evolution of interlocking cast glass blocks towards more curved geometries of equal mass distribution. From left to right: interlocking glass brick inspired by the LEGO® block by [40], osteomorphic block by [42] and osteomorphic block by [30].

Table 6
Assessment of the different interlocking block types by [30].

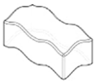
Block type	A	B	C	D	E
					
Interlocking mechanism	Smooth curves	Smooth curves	Male and female blocks	Sliding blocks – intense curves	Semi-sphere (intense) keys for vertical stacking – ability to rotate
Shear capacity	High	High	Moderate	Moderate	Moderate to high
Self-alignment/damping	High	High	High	Low	High
Multifunctionality	High	High	Moderate (cannot accommodate corners)	Moderate (cannot accommodate corners)	Very high (due to rotation, many geometries can be achieved)
Homogeneous cooling in casting	Effective	Effective	Risk of internal residual stresses	Risk of internal residual stresses	Effective
Ease of assembly	High	High	Moderate	Moderate	High
Peripheral structure	Needed	Needed	Needed	Needed on top	Needed on top

Fig. 36. Physical prototypes of different interlocking geometries by [30].

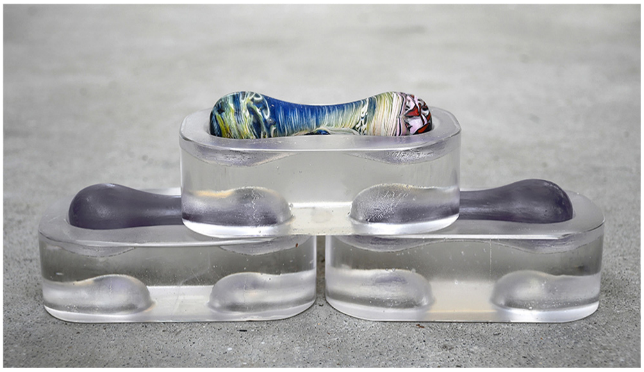


Fig. 37. Physical prototypes of different interlocking geometries by [30].

process that is prohibiting for commercial structural components. Hence, the real breakthrough in cast glass structures will be when a low-expansion glass recipe with low production cost is introduced [44] that will eliminate the size constraints and post-processing of soda-lime and borosilicate glass and allow for faster cooling and thus as well for a faster and more economical production.

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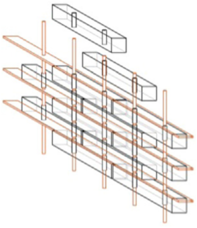
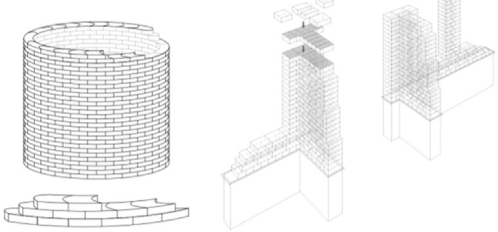
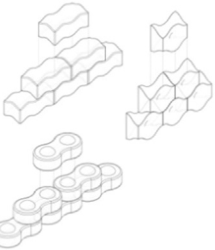
Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Table 7
Design principles of the different structural systems employing cast glass components.

1. Additional substructure	**2. Adhesively bonded glass structure**	**3. Interlocking cast glass units**
Tensile forces are carried by a metal substructure	*Homogeneous load transfer in the glass assembly via rigid adhesive*	*Stiffness is obtained by the interlocking geometry*
		
Dry-assembly/adhesively bonded Interlayer accommodates size deviations Easily assembled Compromised transparency Reversible	Adhesively bonded Adhesive's thickness requires high precision in unit size Meticulous, intensive labour of high precision High transparency Non-reversible	Dry-assembly Interlayer accommodates size deviations Easily assembled High transparency Reversible

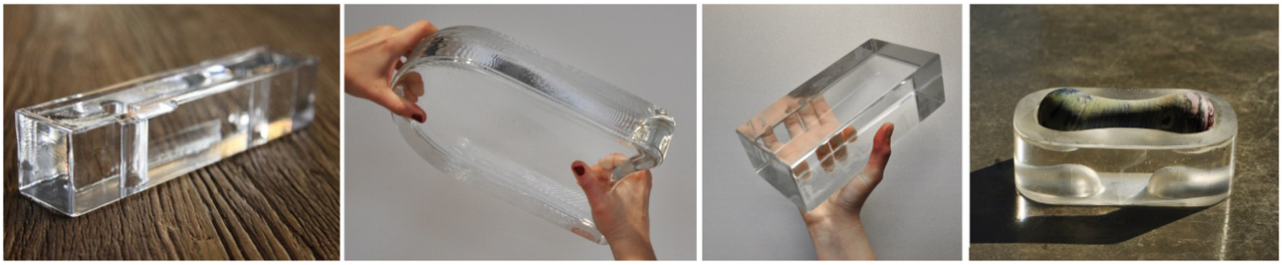
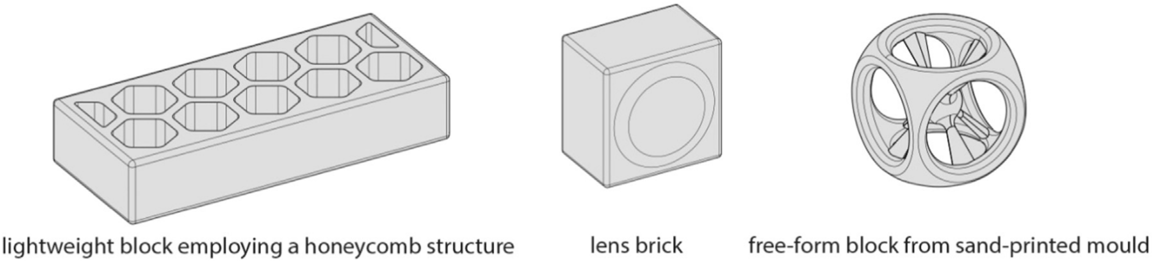


Fig. 38. Left to right: Glass block units employed in the *Optical House, Atocha Memorial, Crystal Houses* and interlocking research.



lightweight block employing a honeycomb structure

lens brick

free-form block from sand-printed mould

Fig. 39. Schematic illustration of new concepts for structural cast glass components.

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