2 Material compositions and production methods for solid cast glass components

Overview of the current production methods and chemical compositions of cast glass[4]

Glass can be made by different manufacturing processes and by numerous of varied recipes that in return provide the material with different properties. Owing to their workability in lower melting temperatures and the corresponding decreased manufacturing costs, soda-lime and borosilicate glass types are preferred for cast glass applications in structures. Glass can be cast in two ways: primary and secondary casting. In primary casting, glass is molten from its primary raw ingredients, whereas in secondary casting, solid existing pieces of glass are re-heated until the (semi-) liquid mass can flow and be shaped as desired. The main process of primary casting is hot-forming (melt-quenching) and of secondary casting is kiln-casting. The principal difference between the two methods, besides the initial state of glass, is the required infrastructure. In hot-forming, molten glass from a furnace is poured into a mould and is then placed in another, second furnace for annealing. In contrast, kiln-casting employs a single kiln for the melting of the (already formed) glass into the moulds and for the subsequent annealing process and requires lower operating temperatures. In both methods the annealing process is similar. The annealing schedule is influenced by numerous factors that cannot be easily simulated as a complex non-linear time dependent multi-variable analysis is required. As a result the annealing schedule of large 3-dimensional cast units is commonly empirical. Different mould types, disposable or permanent, can be used for casting glass objects. The choice of mould mainly depends on the production volume and desired level of accuracy of the

4 This chapter has been published as part of the review article: Oikonomopoulou F., Bristogianni T., Barou L., Veer F., Nijsse R. 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. Journal of Building Engineering, vol.20, 2018.(Oikonomopoulou et al. 2018c)

glass product, and is in practice usually cost and time driven. Currently, there is no standard to determine the design strength of solid cast glass objects for structural applications in architecture. Based on the assumption that the increased volume of cast glass can lead to a higher amount of randomly distributed flaws in the meso-structure, the bending strength of cast glass is expected to be comparable but slightly less than that of standard float glass.

2.1 Introduction

Cast glass may have been the oldest form of glass-making, yet, at present it is rarely employed for architectural applications. This chapter serves as an introduction to casting as a manufacturing process for glass. Accordingly, the most common glass and mould types are presented and the main casting processes are described. The annealing process is explained, highlighting the different factors that can influence the annealing schedule of a cast object. Finally, the properties of cast glass as a structural material are discussed in comparison to standard float glass.

2.2 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 (quartz) glass. Table 2.1 presents the typical chemical composition and characteristic applications of each glass type. An extensive description of the different glass types can be found in (Shelby 2005; Shand, Armistead 1958).

TABLE 2.1 Approximate chemical compositions and typical applications of the different glass types as derived from (Shand,Armistead 1958).

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. Poor resistance to strong alkalis (e.g. wet cement)	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 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 TV screens (CRT) 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 Telescope mirrors
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

Soda-lime is the most common and least expensive glass type (Corning Museum of Glass 2011d). 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 considerably lower thermal expansion coefficient which increases the resistance to thermal shocks and reduces 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 (Thwaites 2011). Due to its ability to absorb X-rays, lead glass is employed as well for nuclear block applications. On the downside lead glass has limited thermal shock and high temperature resistance to and is susceptible to scratching due to its softness; thus it is not considered suitable for architectural applications. Aluminosilicate glass, 96% silica glass and fused silica glass can sustain much higher operating temperatures and heat shocks than borosilicate glass; however they require significantly more energy for their production due to the considerably higher temperatures required for their forming, (Table 2.2), which in turn increase substantially the manufacturing cost[5].

TABLE 2.2 Approximate properties of the different glass types of Table 2.1 based on (Shand, Armistead 1958)*. Mean Melting Point at 10 Pa.s as stated by (Martlew 2005).

Glass type	Mean melting Point at 10 Pa.s*	Softening Point	Annealing Point	Strain Point	Density	Coefficient of Expansion 0°C - 300°C	Young's Modulus
	[°C]	[°C]	[°C]	[°C]	Kg/m³	10^{-6}/°C	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

** 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.*

5 The considerably higher operating temperatures also lead to a significantly reduced life-span of the furnace that further increases the manufacturing costs. Communication with the industry (AGC Belgium) has suggested that a furnace used for melting aluminosilicate glass has approximately half the life-span compared to a furnace used to melt soda-lime glass due to the faster deterioration of the refractory material. For a clear depiction of the difference in the required operating temperatures, refer to Fig. 2.18: Approximate viscosity versus temperature curves plot for the most characteristic glass families described in tables 2.1 and 2.2 based on (Shand,Armistead 1958).2.16 which shows the viscosity versus temperature curves for the most characteristic glass families described in Tables 2.1 and 2.2.

Hence, such glasses are used in specialized applications, such as mobile telephone screens (aluminosilicate) and spaceship windshields (fused-silica)(Corning Museum of Glass 2011a).

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. Due to its reduced hardness lead glass is not recommended for architectural applications. Subsequently, for cast glass applications in architecture, soda-lime and borosilicate glass are the prevailing types.

In the experimental part of this research, soda-lime silica glass is chosen for the manufacturing of prototypes, since, it is the most common and least expensive glass type in the building industry[6].

2.3 Prevailing glass manufacturing processes and current dimensional limitations

Based on its manufacturing process, glass for building industry applications can be shaped as a flat, extruded or solid element. From these methods, float glass is the prevailing type in the building industry. An additional, yet currently only developed within research context, manufacturing method for glass is 3D-printing. Below, the main processes and the corresponding current dimensional limitations for each manufacturing method are briefly presented. It can be concluded that cast glass is the only manufacturing method at present that allows for the creation of solid glass components with a considerable cross-section in 3 dimensions.

6 Soda-lime glass is a more economic option compared to borosilicate glass due to the already considerably higher demand and vast availability of this type of glass and the corresponding raw material. Also, owing to its lower melting point, soda-lime glass requires less energy to be produced, which further decreases the involved manufacturing costs.

2.3.1 Float glass

Flat glass is currently the prevailing type of glass for the building industry. At present, 90% of the flat glass is produced by the float glass method (Bourhuis 2014). The main advantages of this process, introduced in 1959 by the *Pilkington Brothers*, is its relatively low cost, wide availability, superior optical quality glass and large size of glass sheets. A schematic representation of the (soda-lime) float glass process can be seen in Fig. 2.1.

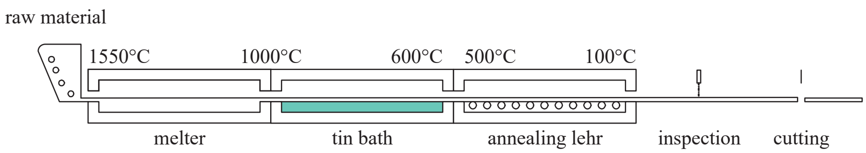

FIG. 2.1 Schematic illustration of the float production process by (Louter 2011) based on (Wörner et al. 2001).

In this continuous float glass process the raw materials are melted in a furnace at ~1550 °C. The molten glass is poured at ~1100 °C onto a bath of molten tin. Being less dense, the glass floats and forms a continuous glass ribbon (approximately 6 mm thick) with perfectly smooth surfaces of the desirable thickness (Fig. 2.2). The thickness of the glass can be adjusted through top rollers in standard thicknesses between 2 and 25 mm[7].

Upon leaving the tin bath the glass has cooled down to ~600 °C. At this temperature range glass has become a solid ribbon which is drawn into a cooling oven, the annealing lehr. In the annealing lehr the solid glass ribbon is carried on rollers over a length up to 150 m so that it is slowly and controllably cooled down to 100 °C, preventing the generation of residual stresses. Once the glass has left the annealing lehr it is inspected by an automated process for visual defects, which are subsequently removed in the cutting process. Finally, the glass is cut to its final size by automated diamond wheels. The sides of the glass ribbon are also slightly cut to

7 Float glass is produced in standard thicknesses of 2, 3, 4, 5, 6, 8, 10, 12, 15, 19 and 25 mm. In practice, the thickness (for building applications) ranges from 4 to 19 mm. 25 mm thick glass is rarely produced (for example currently in Europe only the Cuneo float line of AGC produces 25 mm thick glass). Reasons include the comparatively much slower cooling and annealing process and complications with the cutting of the excessive edge of the float ribbon.

remove any marks of the rollers used to adjust its thickness in the tin bath (Bricknell 2010). The standard float glass size is 6 x 3.21 m (Fig. 2.3), but larger (oversized) plates (Fig. 2.4) can be obtained as well[8]. Yet, the maximum commercial thickness of the float glass panels remains 25 mm.

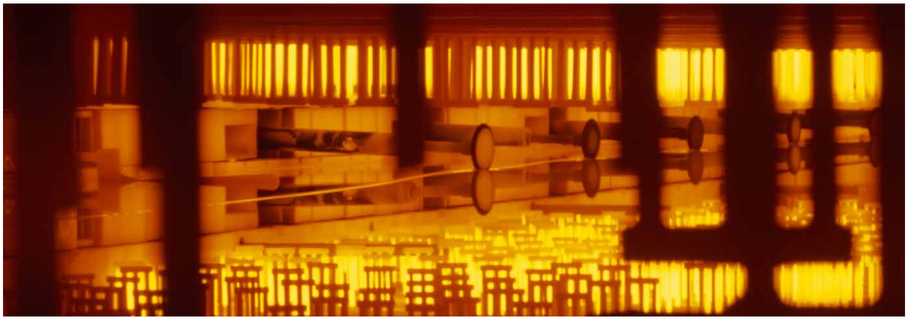

FIG. 2.2 Float glass ribbon within the tin bath. Source: https://www.skyre-inc.com/applications/hydrogen-recycling/

FIG. 2.3 Glass structure out of standard float panels up to 6 m in length by *EOC Engineers* in Philadelphia, USA.

8 The maximum size of float glass panels has been continuously increasing over the last years(O' Callaghan, Marcin 2009). Currently oversized plates up to 20 m in length and 4 m in width can be obtained.

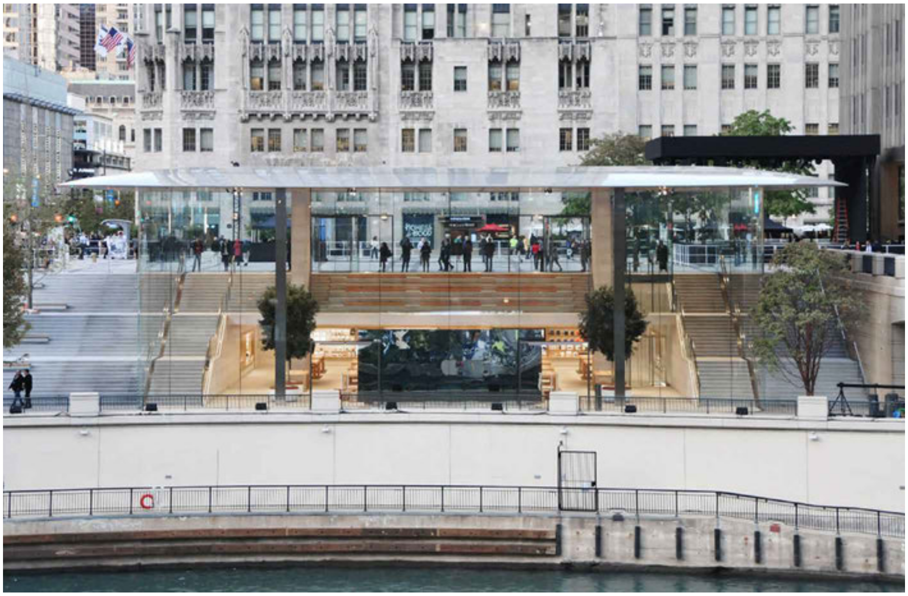

FIG. 2.4 The *Apple Store* in Chicago by *EOC Engineers*. Panels are 3 m wide and up to 10 m in height. Source: *EOC Engineers*.

2.3.2 Extruded glass

Glass extrusion is used to produce glass profiles such as (thin wall) tubes, rods or other glass elements with a constant cross-section. Extruded glass profiles are mainly used in interior architecture, art, design and lighting solutions. Extrusion can be used for glasses with a steep viscosity curve, increased tendency to crystallize and/or a considerably high softening point, such as silica glass (Roeder 1971). Extrusion is an economical method for producing various types of full or hollow profiles with sharp-edged cross sections for industrial use (Pfaender 2012). The most common method for a continuous drawing of tubing is the *Danner process* (Fig. 2.5): A continuous strand of molten glass flows onto a rotating, slightly downward pointing mandrel. Air is blown down a shaft through the middle of the mandrel, creating a hollow space in the glass as it is drawn off the end of the mandrel by a tractor mechanism. The diameter and thickness are controlled by regulating the air flow rate and the speed of the drawing machine. This process allows for a wall thickness of up to 10 mm (Haldimann et al. 2008). After being redirected horizontally, the solidifying tube is transported on a roller track to the pulling unit and is cut into sections of, typically, 1.5 m in length.

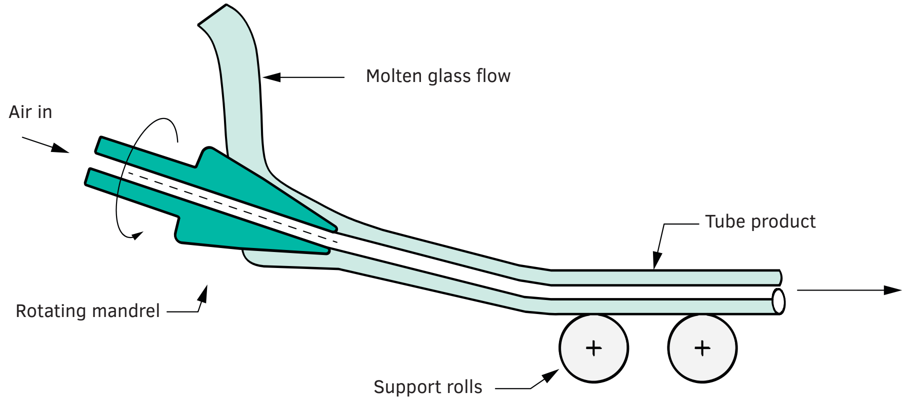

FIG. 2.5 Principle of the Danner process.

The more recent centrifuging process allows for the production of relatively large sections and non-rotationally symmetrical items by spinning: Molten glass is fed into a steel mould that rotates at the required speed. At high speeds, the glass can assume almost cylindrical shapes. When the glass has sufficiently cooled, rotation stops and the glass is removed. This process is more expensive than the Danner production method.

Another important process is the *Vello process*, which has a similar output as the *Danner process*. Molten glass from the furnace flows downward through an orifice (ring). The hollow space in the glass is maintained by a pipe with a conical opening located within the ring. The tube, which is still soft, is redirected horizontally and is drawn off along a roller track, cooled and cut as in the aforementioned process.

Currently, the leading manufacturer of extruded glass profiles is *SCHOTT AG*. The profiles come in a standardized length of 1.5 m but can be customized up to 10 m in length. At present, the standard production of *SCHOTT AG* includes hollow tubes up to 465 mm in diameter and 7 mm thick and solid rods up to 30 mm in diameter (SCHOTT AG 2017).

A great example of the architectural potential of glass rods is the window installation for the *S.C. Johnson Building* in USA (Fig. 2.6), designed by American architect *Frank Lloyd Wright*. The structural potential of the rods has been exhibited in the design and testing of a glass bundle (Fig. 2.7) by (Oikonomopoulou et al. 2017b) which was later applied in the glass truss bridge (Fig. 2.8) as described in (Snijder et al. 2018).

FIG. 2.6 Extruded hollow tubes used at the facade of the *Johnson Building* in USA.

FIG. 2.7 Left: 1.5 m long bundled glass columns at *TU Delft Glass Lab*. Top right: Extrusion profiles made by *SCHOTT AG*. Bottom right: A bundled glass column made of adhesively bonded extruded profiles developed by (Oikonomopoulou et al. 2017b).

For the *GlassTec 2018 Fair* the *TU Delft Glass & Transparency Group*, in collaboration with *Arup*, *SCHOTT AG* and *RAMLAB* developed two novel glass structures utilizing glass rods and tubes: A *glass swing* (Fig. 2.9), created from glass struts, each composed of five glass rods that are pre-stressed by an internal (central) steel bar (Snijder et al. 2019) and a *glass sandwich floor* (Fig. 2.10), where the core elements are extruded glass tubes. The engineering of the latter was based on the concept for glass sandwich panels developed by (Vitalis et al. 2018).

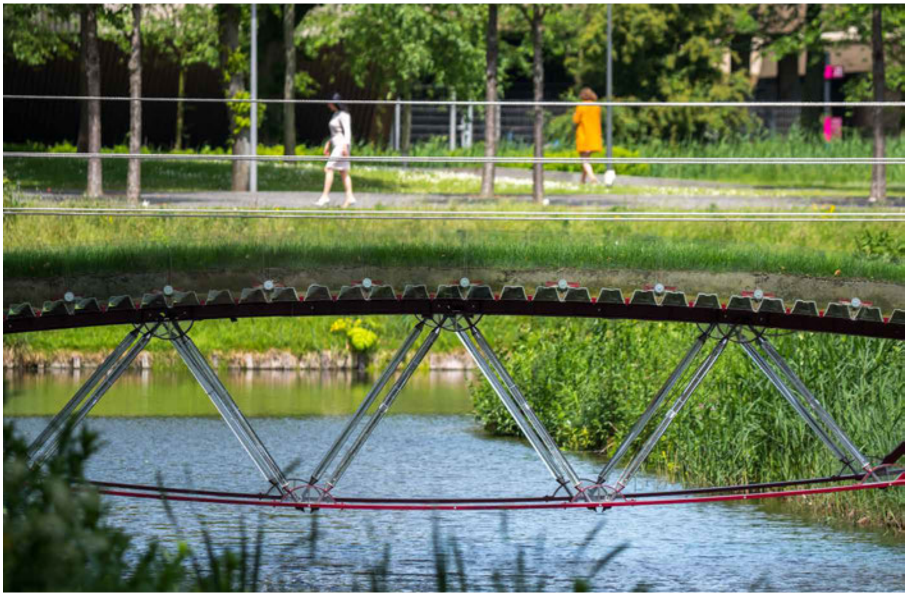

FIG. 2.8 The *glass truss bridge* at the *TU Delft campus* made of extruded glass profiles as described in (Snijder et al. 2018).

FIG. 2.9 The glass swing developed by (Snijder et al. 2019) from *TU Delft*, in collaboration with *Arup*, *SCHOTT AG* and *RAMLAB* for the *GlassTec 2018* exhibition.

FIG. 2.10 The glass sandwich floor developed by the *TU Delft Glass & Transparency Lab*, in collaboration with *Arup* and *SCHOTT AG* exhibited at *GlassTec* 2018.

2.3.3 3D-printed glass

3D-printing of glass is still in an infant stage of development. A glass 3D-printing method (G3DP) for optically transparent soda-lime and coloured glass has been recently developed by the *Mediated Matter Group* in collaboration with the *Department of Mechanical Engineering* and *Glass Lab* of *MIT*. The platform is based on a dual heated chamber concept. The upper part acts as a Kiln Cartridge; it operates at ~1040°C and pours the molten glass through a nozzle to the desired shape (Fig. 2.12). The object is built within the lower annealing chamber[9] which keeps the glass hot enough so that the next layer of structure would adhere to it while the glass can cool down controllably (Klein 2015) (Fig. 2.11).

9 The temperature of the annealing chamber is set at 480° C, slightly below the glass annealing temperature of 515 °C, since the glass heat radiation contributes to an increase of the environmental temperature (Klein 2015).

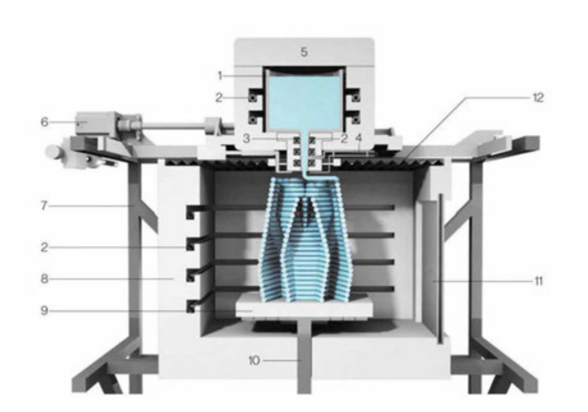

FIG. 2.11 Rendered cross-section of the Kiln Cartridge by (Klein 2015).1.crucible 2.heating elements 3.nozzle 4.thermocouple 5.removable feed access 6. stepper motor 7. printer frame 8. print annealer 9. ceramic print plate 10. z-driven train 11. ceramic viewing window 12. insulating skirt.

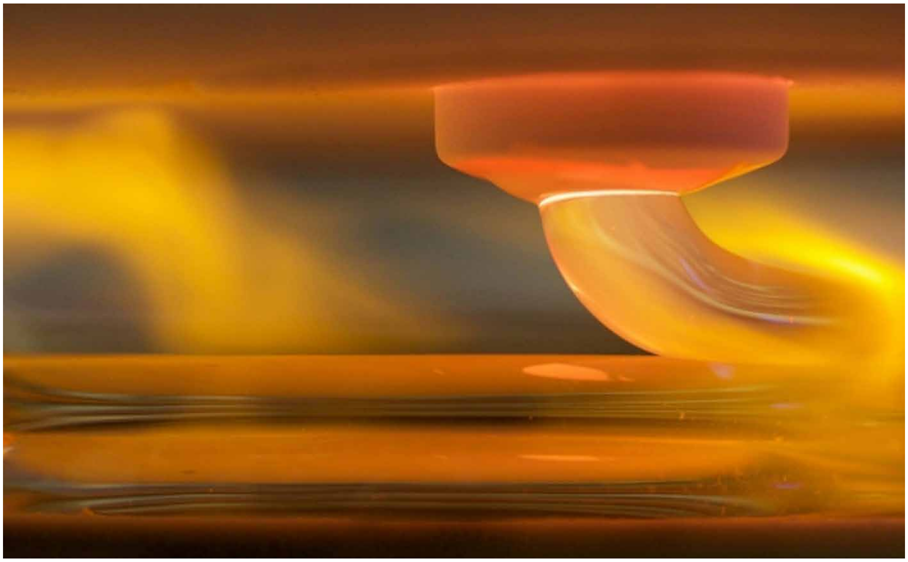

FIG. 2.12 Glass 3D-printing nozzle. Source: Steven Keating.

The process was further developed to a larger-scale additive manufacturing technology (G3DP2) for building components made of silicate glass with tuneable and predictable mechanical and optical properties. G3DP2 includes a digitally integrated thermal control system to accompany the various stages of glass forming and a 4-axis motion control system permitting flow control, spatial accuracy and precision and faster production rates with continuous deposition of up to 30 kg of molten glass (MIT Media Lab 2018). The potential of the new method has been demonstrated by the construction of a series of 3m-tall free-standing, pre-stressed glass columns consisting of 15 segments each (Fig. 2.13 and Fig. 2.14). The columns do not carry any weight other than their own in the installation. 3D-printing of glass has a high potential in creating components with variable thicknesses and complex inner features. Nonetheless, it faces the same challenges with the annealing of glass objects (discussed in detail in Chapter 2.4) as cast glass. In consequence, 3D-printing of (soda-lime) glass can only occur within a highly controlled annealing chamber: the glass object has to be cooled down to room temperature in a slow and controlled way to release permanent stresses associated with thermal gradients that otherwise would lead to the spontaneous breakage upon cooling. Hence, the glass object is confined to the size of the annealing chamber.

FIG. 2.13 3m tall glass prototypes out of 3D-printed segments. Source: *Paula Aguilera*, *Jonathan Williams* and The *Mediated Matter Group*.

FIG. 2.14 An array of 3D-printed glass components prepared in a 3x5x3 array ordered for assembly. Source: *The Mediated Matter Group*.

2.3.4 Cast glass

Cast glass is currently the only method that allows for the creation of 3-dimensional glass objects of a substantial, monolithic cross-section and/or of complex geometry. By pouring molten glass into moulds, solid 3-dimensional components can be made of virtually any size. Moulds can be either disposable out of a soft material such as silica plaster or permanent ones out of steel or graphite. There are two main processes for cast glass: primary casting and secondary casting: In the former, glass is founded as a hot liquid from its raw materials, whereas in the latter, glass already formed in solid pieces is remolten to a temperature where it can flow and be shaped to the desired object.

Glass casting has been commonly used in the fields of art and astronomy. Currently the largest monolithic cast glass objects are the mirror blanks of the Giant Telescopes. Characteristic examples include the *Giant Magellan Telescope* blanks, each 16 t in weight and the *Hale Telescope* blank (Fig. 2.15), weighing 20 t[10]. Cast glass has been so far employed in structural applications in architecture in the form of solid blocks, commonly between 2 - 8.4 kg in weight. Characteristic examples are the *Atocha Memorial, Crown Fountain, Optical House* and the *Crystal Houses*[11]. Same as with 3D-printing glass the main obstacle with cast glass of considerable dimensions is the time-consuming annealing process. As an example, the successful annealing of the aforementioned *Hale Telescope* blank required 10 months. Table 2.3 provides an overview of the current glass fabrication methods with applications in the building industry.

The current size limitations in the float and extruded processes result in virtually 2-dimensional glass objects of high slenderness ratio. 3D-printed and cast glass are thus, at present, the only methods that can result in essentially, free-form, 3-dimensional glass elements of a substantial thickness. These two processes follow the same basic principle: Molten glass is poured to form a glass object that cools controllably to room temperature into an annealing chamber or kiln. The fundamental difference is that in casting, glass is poured into a mould of the desired shape, whereas in 3D-printing, glass is directly deposited as a viscous fluid that forms a continuous layered construction. On account of the layered nature of a 3D-printed object the overall transparency is compromised. The biggest drawback though of 3D-printing glass is that it is, at present, approx. 30 times slower than

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10 For a more in-depth analysis of the largest cast glass monolithic objects please refer to Chapter 3.

11 For a more in-depth analysis of the existing glass structures with cast blocks please refer to Chapter 4.

cast (and pressed) glass (Klein 2015). Advantages of 3D-printing include the mass-customization and design freedom of the final object. To this end, under the assumption of fully developed processes for 3D-printing and casting of glass, the former would be preferred for customized solutions and the latter for the mass fabrication of identical units. Nevertheless, the creation of cheap, disposable moulds[12] can render cast glass a competitive solution for customized components as well that also exhibit a higher level of transparency compared to 3D-printed ones.

Overall, it can be concluded that casting provides currently the greatest freedom in the volume and size of the resulting glass object.

TABLE 2.3 Overview of existing glass fabrication methods for building components and their current size limitations.

Glass process	Optical Characteristics	Main type of glass applied	Standard size [mm]	Thickness [mm]
Float	Smooth Transparent	Soda-lime	3210 x 6000[a]	2-25
Extruded	Smooth Transparent	Borosilicate Silica	1500-10000 in length	Hollow: 460 Ø Solid: 300 Ø
3D-printed	Layered Transparent	Soda-lime	currently up to 30 kg	currently approx. 30 mm[b]
Cast	Smooth Transparent	Soda-lime Borosilicate Lead	currently up to 20000 kg[c]	n/a

[a] *The max. panel size is continuously stretching. At present, up to 20 m long panels have been produced.*
[b] *Based on the work of (Klein 2015)*
[c] *Weight of the Hale Telescope monolithic glass blank. For more information please refer to chapter 3.2.*

12 An overview and discussion on the different mould types for cast glass can be found in Chapter 2.5

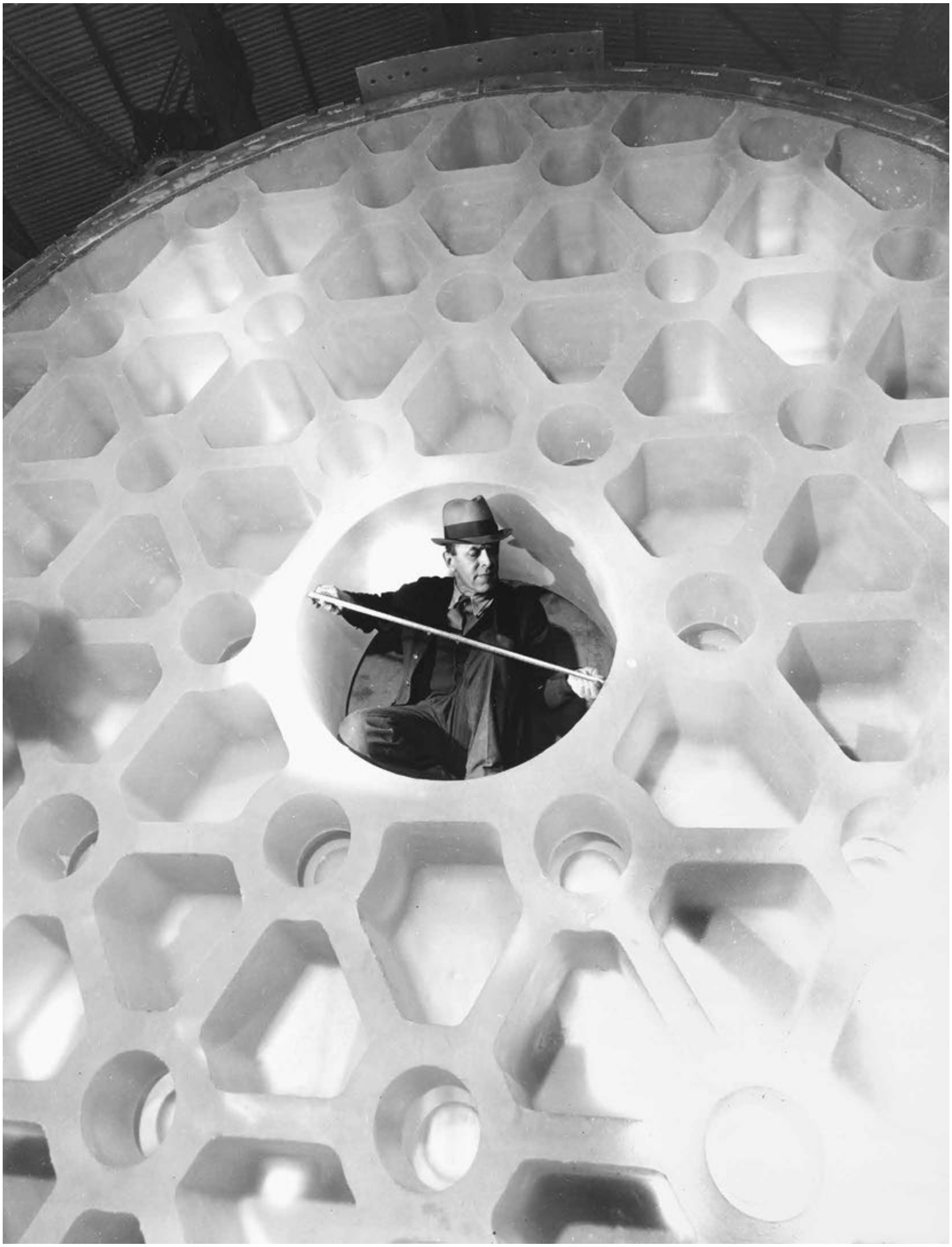

FIG. 2.15 The cast glass blank of the Hale Telescope. Image credits: Collection of the *Rakow Library, The Corning Museum of Glass.*

2.4 Casting and annealing process

2.4.1 Prevailing casting processes

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 formulated in solid pieces (i.e. sheet, rods, marbles, grains, powder) is re-heated until it can flow and be shaped as desired (Cummings 2002). Thus, the secondary process requires lower operating temperatures compared to those for founding glass.

The main process of primary casting is hot-forming (melt-quenching) and of secondary casting is kiln-casting (Fig. 2.16). 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 (Bristogianni et al. 2017). 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.

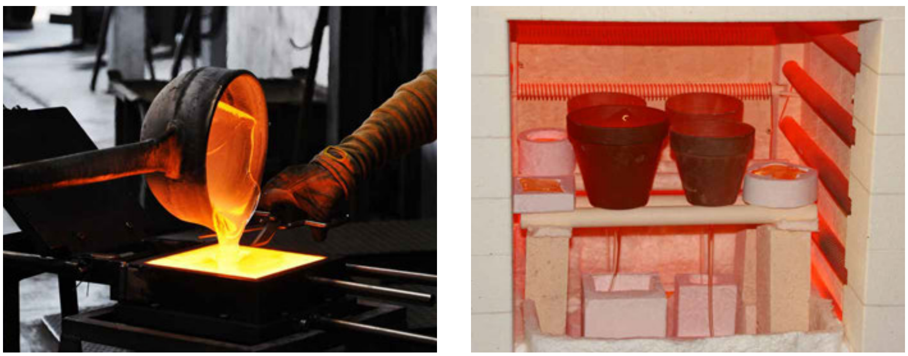

FIG. 2.16 Left: Primary casting method (hot-forming). Right: Secondary casting method (kiln-casting).

2.4.2 Annealing Process

In both methods, the annealing process is similar. Initially glass is heated until it is viscous enough to flow into the mould. The viscosity of the glass at that point is expected to be between 10 and 10^3 Pa.s, defined as melting temperature and working point of glass correspondingly (Martlew 2005). Once the mould is filled, the glass is rapidly cooled to a few degrees (typically around 20° C) below its softening point[13]. This rapid cooling stage, named quenching, is essential for preventing a crystal molecular arrangement of the melt (see Fig. 2.17). During this phase, the glass's relatively low viscosity allows any induced thermal stress to relax to a negligible amount immediately (Shelby 2005). When the glass temperature drops below the softening point, the viscosity of glass is sufficient for it to retain its shape and not deform under its own weight[14] (Shand 1968). 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[15]. 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 (Shand, Armistead 1958). At this temperature range, stress can be relieved due to the viscous flow of the material that allows for molecular rearrangements. In particular, at the annealing point stress relief can occur within a few minutes; whilst towards the strain point it requires a few hours[16] (Bray 2001). Effectively, below the strain point, stress is unable to relax in time and is considered permanent (Watson 1999). 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 (Shand, Armistead 1958). Fig. 2.17 provides a

13 The softening point is defined as the temperature at which the heated glass, supported at each end, begins to sag under its own weight. It must be stressed that even with the exactly same glass, this temperature can slightly vary according to the weight and thickness of the object to be annealed (Bray 2001).

14 For crystals, transition from solid to liquid occurs exactly at the melting temperature (Tm). Unlike crystals glass has no fixed melting point. Instead it gradually softens and stiffens as the temperature changes. The viscosity of the glass changes with temperature (Schott AG 2004). In this study wherever melting temperature is referred to, it actually concerns a temperature range where viscosity of glass corresponds to approximately 10 Pa.s

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

16 A small amount of residual stress is acceptable for the majority of glass types, but for optical glass in particular it should be reduced to the minimum. This means that optical quality glass of considerable thickness such as the one required for the giant telescope mirrors, discussed in chapter 3, may require several months of annealing. For example, the Mt Palomar telescope lens, was cooled from 500°-300° C at the rate of 1° C a day drop (Cummings 2001).

typical curve for viscosity as a function of temperature for soda-lime glass, indicating the above discussed key temperature points (strain, annealing, softening, working). In Fig. 2.18 the viscosity versus temperature curves of the most characteristic glass families can be seen. A schematic diagram of a typical annealing scheme for soda-lime glass based on (Shand, Armistead 1958) is shown in Fig. 2.20.

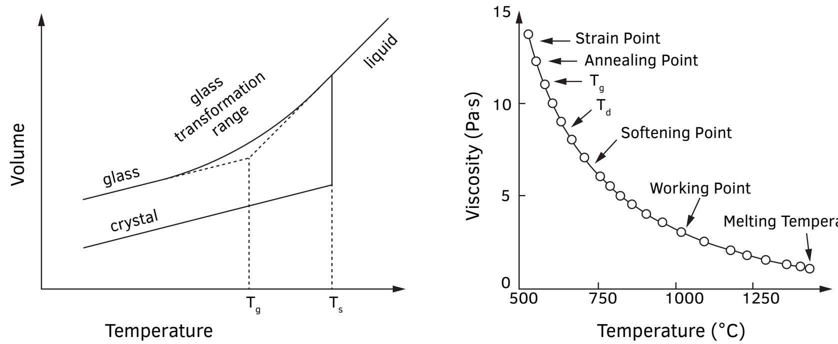

FIG. 2.17 Left: Schematic representation of the volume's dependence on temperature for a glass and a crystalline material. During the cooling process from a liquid to a solid, glasses do not convert to a crystalline state. Right: Typical curve for viscosity as a function of temperature for a soda-lime-silica melt (NIST Standard No. 710). Defined viscosity points are indicated on the figure. Source: (Shelby 2005).

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. This in turn is related to the amount of surfaces exposed to cooling, the type of glass and its coefficient of expansion, the thickness of the section (Fig. 2.19) and the amount of residual stress required (Shand, Armistead 1958). Accordingly, round or ellipsoid shapes and equal mass distribution are key aspects for the prevention of residual stresses[17] and are thus preferred over sharp, pointy edges and shapes with uneven volume distribution 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, the amount of surfaces exposed to cooling, the amount of other thermal masses in the furnace, even the

17 Variations in the thickness of a glass object result in different temperatures within the glass that in turn lead to different shrinkage rates within the component causing strain.

geometry and characteristics of the furnace itself (Watson 1999). For example, a piece of flat glass resting on a kiln shelf with only one side exposed would need twice the annealing time than a piece of glass with both sides exposed would require[18]. Castings almost completely enclosed within a mould tend to cool more homogeneously: the mould material functions as an insulating material that restricts the heat loss, reducing considerably the differential between exterior and interior temperatures of the glass (Bray 2001). In contrast, in castings made in open moulds (discussed in chapter 2.4), the top, exposed surface tends to cool considerably faster than the surfaces in contact with the mould[19].

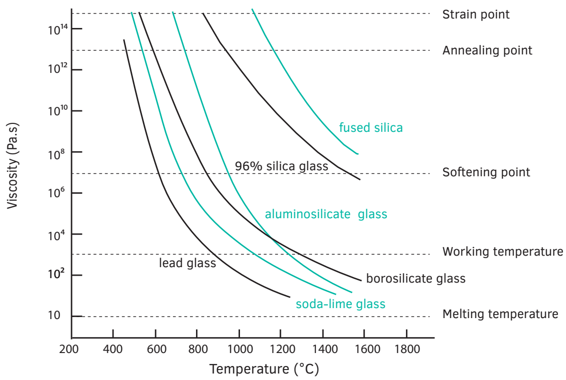

FIG. 2.18 Approximate viscosity versus temperature curves plot for the most characteristic glass families described in tables 2.1 and 2.2 based on (Shand,Armistead 1958).

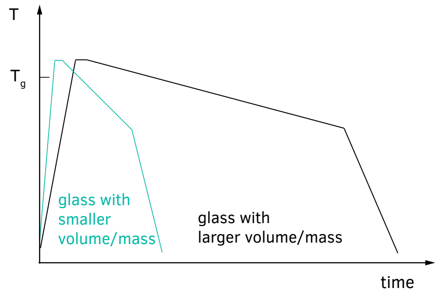

FIG. 2.19 Schematic representation of the annealing temperature as a function of time for glasses of different volume by (Schott AG 2004).

Numerous guidelines exist in the scientific and industrial literature on the annealing cycle of cast objects. Characteristic annealing guidelines based on the glass's thickness, by glass manufacturing companies such as *Gaffer* and *Bullseye* have been developed according to the annealing schedule (Fig. 2.20 and Table 2.4) proposed by (Shand, Armistead 1958) and can be found in the Appendix. (Cummings 2001) and (Bray 2001) provide a comprehensive explanation for the annealing cycle of cast glass artefacts. However, such guidelines are often tailored to specific circumstances

18 According to (Cummings 2001) the thickness of the glass is always the part furthest away from an outside surface. In this way it is considered as annealing from one side only, effectively doubling the thickness and thus the minimum acceptable annealing time.

19 A simple solution to this problem employed by glass artists is to cover the open area of the mould with a slab made of an insulation material such as ceramic fibre, once the glass approaches its annealing point.

and include unclear assumptions (Watson 1999). Thus, even though in theory the desired heat transfer can be calculated, in practice, due all the above mentioned parameters, the annealing schedule of large 3-dimensional cast units is often empirical, based on practical experience (Cummings 2001; Watson 1999).

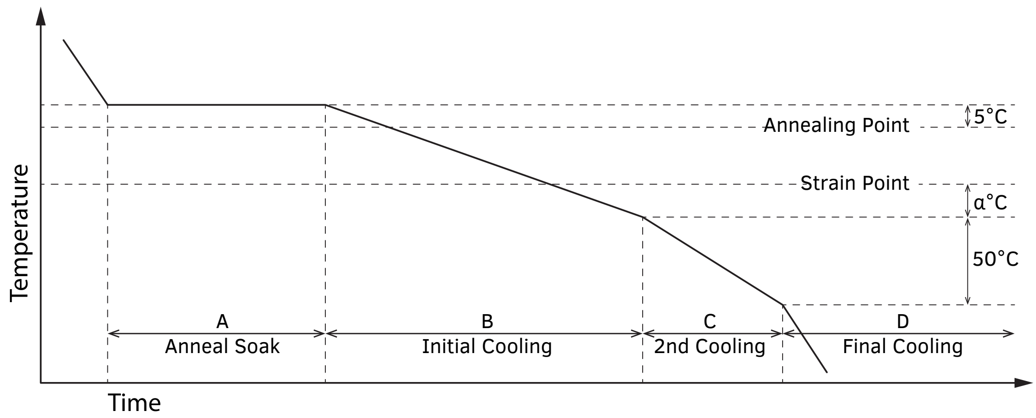

FIG. 2.20 Typical annealing scheme for commercial soda-lime glasses.

TABLE 2.4 Typical annealing scheme for commercial soda-lime glass based on Fig. 2.20, adapted from (Shand, Armistead 1958).

Expansion Coef. of Glass per °C	Glass Thickness [mm]	Cooling on one side					Cooling on two sides				
		A	B		C	D	A	B		C	D
		Anneal soak	Initial cooling (annealing)		2nd cooling	Final cooling	Anneal soak	Initial cooling (annealing)		2nd cooling	Final cooling
		Time [min]	Temp. [°C]	Cool rate [°C/min]	Cool rate [°C/min]	Cool rate [°C/min]	Time [min]	Temp. [°C]	Cool rate [°C/min]	Cool rate [°C/min]	Cool rate [°C/min]
$33*10^{-7}$	3.2	5	5	12	24	130	5	5	39	78	400
	6.3	15	10	3	6	30	15	10	12	24	130
	12.7	30	20	0.8	1.6	8	30	20	3	6	30
$50*10^{-7}$	3.2	5	5	8	16	85	5	5	26	52	260
	6.3	15	10	2	4	21	15	10	8	16	85
	12.7	30	20	0.5	1	5	30	20	2	4	21
$90*10^{-7}$	3.2	5	5	4	8	50	5	5	14	28	140
	6.3	15	10	1	2	11	15	10	4	8	50
	12.7	30	20	0.3	0.6	3	30	20	1	2	11

2.4.3 Measuring stresses in cast glass objects

In solid cast components with a considerably larger thickness than standard float glass plates, an accurate through-the-entire-thickness stress measurement by a *Scattered Light Polariscope (SCALP)* stress-meter (using the current hardware/ software) is not yet fully possible[20]. In such cases, the effectiveness of annealing is normally qualitatively evaluated with the use of a polariscope. If the glass element is subjected to stress, it exhibits optical anisotropy. This corresponds to two refractive indices, which result in the presence of isochromatic fringes (coloured patterns) when polarized light passes through the component (see Fig. 2.21, right) (McKenzie,Hand 2011).

FIG. 2.21 Qualitative analysis of strain concentration by polarization test. Bricks such as the ones shown on the right have a clear indication of residual stresses. Elements with grey-scale spectral composition, such as the one on the left, have low residual stresses.

(Shribak 2015) provides an extended analysis of the interference colours seen through polarization. For small retardance the brightness of the region increases, first with a white spectral composition at 200nm. As the retardance increases,

20 Over the last few years elaborate equipment has been developed for determining the stress levels in glass bottles and containers. Such polarimeters like the *StrainScope®* by *Ilis* can indicate the level of mechanical stress in the examined glass objects. Nonetheless, a measuring equipment specialized in 3D cast glass objects is yet to be developed and would ideally require a 3D-scanned model of the object that can accurately indicate the magnitude of the residual stresses and the existence of flaws or inclusions at all locations.

colours start to appear beginning with yellow, then red, blue and green. The colour changes in this sequence three more times until the retardance reaches 2000nm. Then the interference colours turn white again and the retardance can no longer be reliably determined using the region's spectral composition. A continuous presence of only black and white subsequently signifies low residual stresses (see Fig. 2.21, left). Accordingly, glass without any stress will appear completely dark (Schott AG 2004). If the specimen presents besides black only grey-scale spectral composition, it has low residual stresses. When the colour spectrum appears the amount of stress is higher but cannot be quantified.

2.5 Mould types

Table 2.5 summarizes the characteristics of the prevailing mould types available for glass casting, illustrated in Fig. 2.22. 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. 2.23), 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 is in kiln-casting.

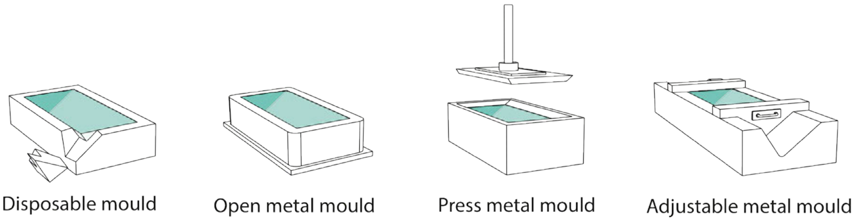

FIG. 2.22 Illustration of the most common mould types.

TABLE 2.5 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	

For a series production, permanent moulds from steel or graphite (Fig. 2.24) are preferred in combination with the melt-quenching technique that is considerably more time-efficient than kiln-casting. With such moulds, significantly increased dimensional 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 if required (Fig. 2.25), to allow for shape flexibility, but this 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.

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FIG. 2.23 Disposable mould out of plaster and silica sand.

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 does 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* (Niehe 2017) for the casting of complex and individually produced steel nodes (Fig. 2.26). Sand casting, which comprises a template (typically made of wood) that is pressed into the sand to make a clear impression, is commonly used by glass artists as a cost-efficient mould solution for casting glass. This technique of low accuracy, however, is not used to produce building elements. Nonetheless, the development of automated, customized 3D-printed sand moulds of high accuracy, [21] can revolutionize the way we design and produce cast glass elements. 3D-printers of sand, such as the ones used by *3Dealize* and *ExOne*, are already employed for the production of sand casting moulds for metal objects (aluminium, steel, iron and magnesium) of high accuracy and complex geometries (ExOne 2019). Research on the use of 3D-printed sand moulds for glass casting by (Flygt 2018) and (Bhatia 2019; Damen 2019) have so far yielded promising results (Fig. 2.27), suggesting that this method can indeed be used as a cost-effective solution of high accuracy for the casting of customized solid glass components or/and of components of complex geometry (e.g. topologically optimized).

21 Based on personal communication with *3Dealize*, 3D-printed sand moulds by *3Dealize* have a size accuracy of ±0.1 mm, defined by the grain size of the sand. 3D-printed sand moulds are currently used for the metal (aluminium, steel, iron, brass, bronze) casting of perplexed components, mainly for the automotive, aerospace, pump and machine industry.

FIG. 2.24 High precision open steel moulds used for the manufacturing of the glass blocks for the *Crystal Houses* façade.

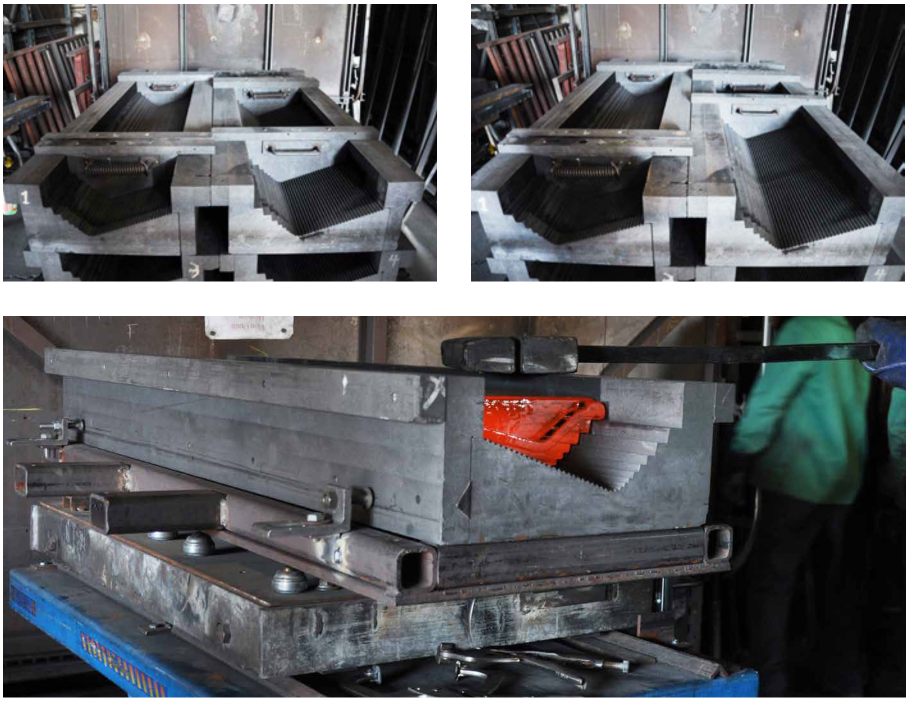

FIG. 2.25 Adjustable graphite mould at *John Lewis Glass Studio* for the components of the *Ice Falls* project by *James Carpenter.*

FIG. 2.26 Cast steel node, designed by Arup, made in 3D-printed sand mould. Source: Arup/Davidfotografie.

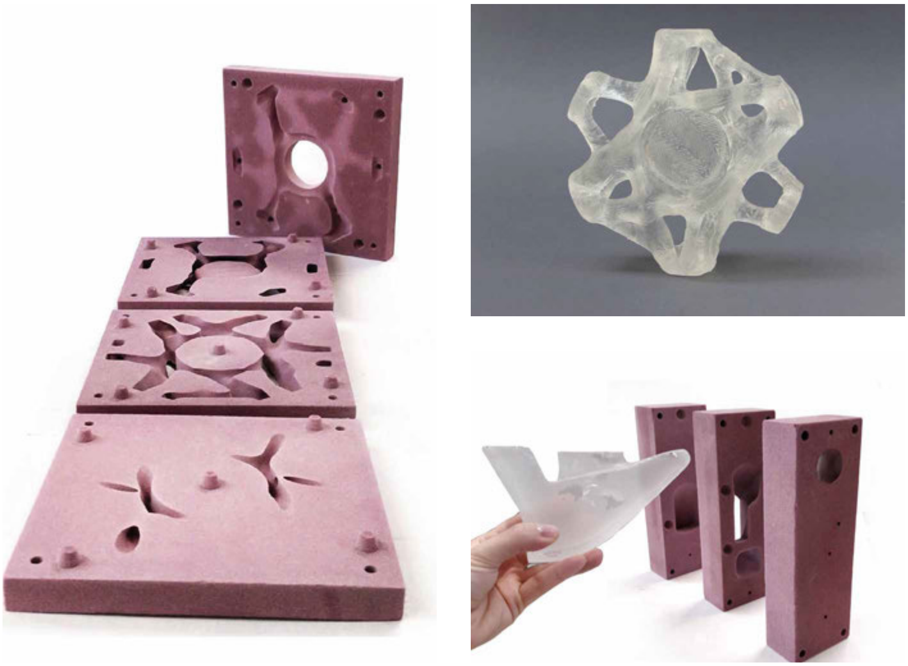

FIG. 2.27 3D-printed sand moulds produced by *ExOne* and the resulting cast glass components for a topologically optimized cast glass grid-shell node by (Damen 2019) (left and top right) and for a structurally optimized cast glass column by (Bhatia 2019) (bottom right).

2.6 Strength of cast glass

A selection of material properties of typical soda-lime silicate and borosilicate glass, the two most prevailing types of cast glass in architectural applications, is presented in Table 2.5. Glass is a brittle material. It has a comparable density to that of concrete and a Young's modulus similar to that of aluminium. Glass does not consist of a geometrically regular network of crystals, but of an irregular 3-dimensional distribution of rings or arches (broken rings)[22] composed of at least 3 tetrahedral modules[23] -each composed of one silicium (Si) atom and four oxygen (O) atoms (SiO_4) - and intermediate alkaline parts (see Fig. 2.28). Thus, glass is an amorphous material. As an amorphous material it presents no crystallographic density variation and no phase boundaries at which the light rays are scattered, thus, it is transparent.

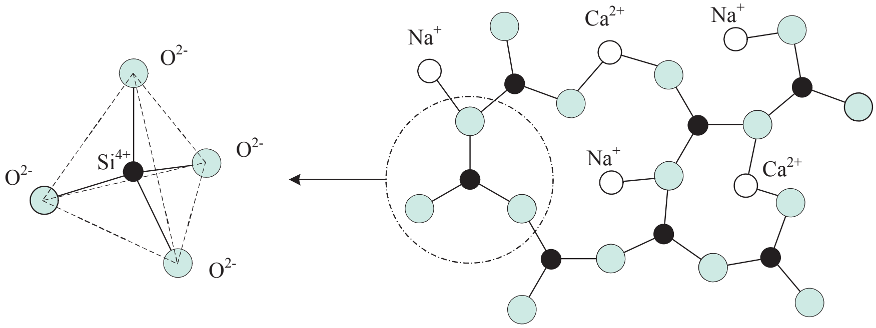

FIG. 2.28 Schematic representation of the structure of soda-lime silica glass based on (Louter 2011).
Left: 3D schematic representation of a tetrahedral module built from one silicium and 4 oxide atoms.
Right: 2D schematic representation of the irregular network of soda-lime silica glass.

The random molecular structure has no crystallographic slip-planes or dislocations to allow macroscopic plastic flow before failure (Overend et al. 2007). Hence, glass exhibits an almost perfectly elastic, isotropic behaviour and brittle failure at

22 A regular ring can be composed of up to 8 tetrahedral units. Where rings are combined due to a non-bridging oxide atom this can be higher; although the local structure is then no longer ring shaped.

23 This statement refers to soda-lime glass, which is the most commonly applied in the built environment. For example, in borosilicate glass the modules are trihedral.

normal temperature. In theory, glass's strength can be defined by the forces of the interatomic bonds. Based on *Orowan's* stress formula, the failure stress σ_m of a material is given by:

$$\sigma_m = \sqrt{\frac{E\gamma}{r_0}}$$

where:

E = Young's modulus
γ = fracture surface energy
r_0 = equilibrium spacing of the atoms

Accordingly, the theoretical strength of typical silica glass (E = 70 GPa; γ = 3 Jm^{-2}; r0 =0.2 nm) amounts to 32 GPa (Shelby 2005). This strength is, however, of no practical relevance for structural applications. In practice, the tensile bending strength of annealed soda-lime glass is effectively 3 orders of magnitude lower. According to EN 572-1:2004 the characteristic bending strength is 45 MPa. This reduction of strength was attributed by (Griffith 1921) to the presence of randomly distributed pre-existing microscopic flaws and geometrical defects which act as stress concentrators. Due to the inability of glass to redistribute stresses by plastic deformation, a small flaw or inclusion can result in local stresses that exceed the theoretical strength, causing the fracture of the glass. Hence, fracture of glasses is governed by the presence of (Griffith) flaws.

TABLE 2.6 Properties of standardized soda-lime and borosilicate glass according to EN572-1:2004

	Symbol	Units	Soda-lime	Borosilicate glass
Density	ρ	Kg/m^3	2500	2200-2500
(Knoop) Hardness	$HK_{0,1/20}$	GPa	6	4.5-6
Young's modulus	E	GPa	70	60-70
Poisson's ratio	ν	-	0.22-0.24	0.2
Thermal expansion coefficient	α_T	10^{-6}/K	9	Class 1: 3.1-4 Class 2: 4.1-5 Class 3: 5.1-6
Specific thermal capacity	c_p	$J{\cdot}kg^{-1}{\cdot}K^{-1}$	720	800

In particular, a glass element will fail as soon as the stress intensity due to tensile stresses at the tip of a flaw reaches its critical value. The strength of a glass specimen is related to the depth of the critical flaw[24]. A larger flaw depth or a sharper flaw leads to lower strength. The flaws display a time-dependent behaviour when loaded in tension due to stress corrosion in the glass. In the presence of humidity or water, flaws grow slowly when exposed to a positive crack opening stress[25]. Accordingly, a glass specimen stressed below its momentary strength will still fail after the time necessary for the most critical flaw to grow to its critical size at that particular stress level (Haldimann et al. 2008). Overall, the stress intensity/time dependant crack growth rate depends on several parameters and is extremely variable[26].

Subsequently, the tensile strength of glass is not a material constant, but it depends on multiple aspects, i.e. on the condition of the surface, the size of the glass element, the action history (intensity and duration), the amount of residual stress and the environmental conditions. Accordingly, the higher the load, or the longer the load duration and/or the deeper the initial surface flaw, the lower the effective tensile strength is (Haldimann et al. 2008). As flaws do not grow or fail when in a purely compressive stress field, the compressive strength of glass is considerably higher than its tensile strength. Nevertheless, the compressive strength of glass is not governing virtually any of the structural applications of the material. Glass will always fail due to exceeding local tensile stresses. Even when a glass element is loaded in compression, peak tensile stresses will develop due to buckling or due to the Poisson's ratio effect long before the compressive strength is reached.

Geometrical defects and flaws are already present during the production process of the material but can be further introduced due to scratching, impact, debris, chemical attack, thermal stresses, etc. Even contact with another piece of the same glass or with metal objects used in the handling and transportation process is sufficient for generating flaws.

Flaws in glass can be divided in 3 regional categories: surface, edge and inclusions (Fig. 2.29). The edge finishing has the major effect on the effective strength of glass (Molnár et al. 2012) due to the more severe surface damage at the edge, result of the cutting and machining process. Thus, the inherent tensile strength of the edge of

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24 At the direction perpendicular to the tensile stress vector.

25 The chemical process associated with stress corrosion can be explained by the classical stress corrosion theory, which embodies the chemical reaction of a water molecule with silica at the (stressed) crack tip. This chemical reaction both sharpens and lengthens the crack tip, which leads to an increase in stress around that area.

26 For an in-depth reading on the fracture strength of glass elements please refer to (Overend et al. 2007; Haldimann et al. 2008).

a glass pane is generally lower than the strength away from the edge (Louter 2011). Flaws at the surface of glass have as well a significant effect on the effective strength of the material, especially if the surface is directly loaded. Defects at the meso-structure (inner volume) can also lead to early failure. Based on the assumption that the flaws are randomly distributed over the glass surface, the chance of the presence of a large critical flaw, meaning a lower failure strength, increases with increasing specimen size (Louter 2011) – this is called the inverse scale effect.

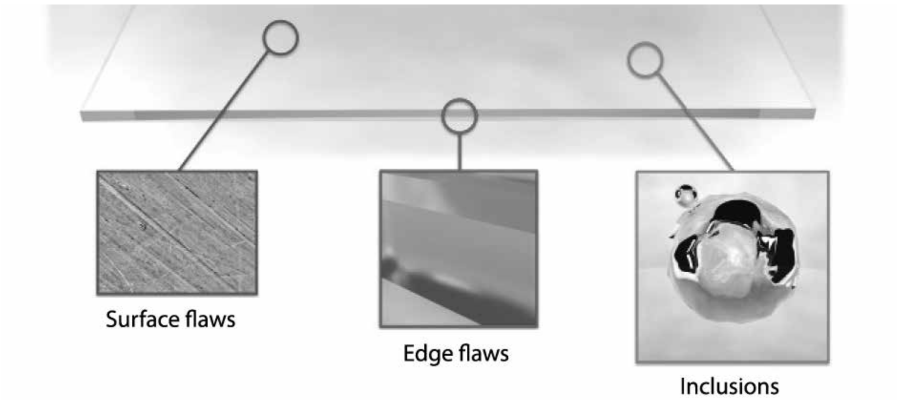

FIG. 2.29 Main glass flaw regional categories. Source: (Molnár et al. 2012)

Flaws in the meso-structure are distinguished by (Bartuška 2008) in three categories (Fig. 2.30):

- gaseous inhomogeneities (bubbles or seeds)
- crystalline inclusions (stones)
- glassy inhomogeneities (cords or striae).

Cords or striae are defined by *ASTM* (*American Society for Testing and Materials*) as glassy inclusions with optical properties differing from the glass matrix. They may be caused by insufficient stirring of the molten material or a chemical reaction in the furnace. Hence, striae is of different composition or may be a result of incomplete fusion of the material. Cords may have different expansion properties to the base glass, which in the occurrence of thermal stresses can lead to failure. At present, there is no extensive physiochemical study of cords and stones. Little regarding their compositions and origins is known.

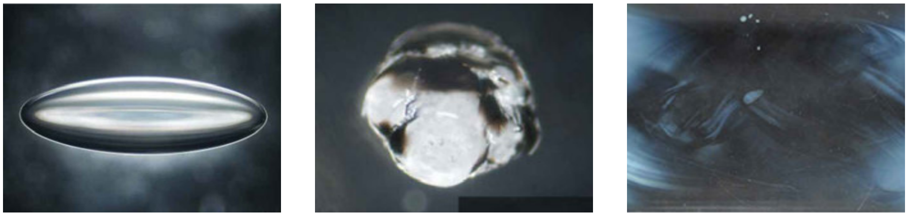

FIG. 2.30 Inclusion flaws in glass. From left to right: Bubbles, stones and cord. Source: (Molnár et al. 2012) and own image (right).

Crystalline inclusions (stones) are imperfectly melted material compounds that are not amorphous. They have a slightly different density than the base glass and exhibit different mechanical properties, different thermal expansion coefficient and almost no light transmittance ability. Such inclusions can be generated due to remains from the batch that have not been completely melted, wall material with low solubility (refractory wall contamination), particles from the surrounding atmosphere, devitrification processes and crystallization. Characteristic examples of inclusions are the nickel sulphide (NiS)[27] inclusions and the refractory wall traces that have been accidentally embedded in the finished glass. NiS inclusions or stones of foreign matter (such as refractory brick) can cause excessive internal stresses in glass due to the differential volume change during thermal expansion/contraction that can further lead to failure.

Air bubbles (seeds) can be generated by various sources, such as the decomposition of the raw materials, nucleation growth, chemical, electrochemical and mechanical reactions. Bubbles that remain in glass can lead to stress concentrating defects (Bartuška 2008). (Molnár et al. 2012) proved numerically that a 1 mm in length bubble could generate a significant strain peak in the glass.

Several standards[28] exist on the physical and mechanical properties of typical soda-lime float glass (Table 2.6). In contrast, there is no standard yet regarding the strength of solid cast glass objects. It is assumed that the cast and float manufacturing processes of glass lead to closely comparable mechanical properties. With proper annealing and processing, the chemical compositions are virtually identical and the occurrence of defects such as air bubbles is limited. In the *Material*

27 NiS inclusions result from the presence of nickel contaminants in the glass melt reacting with sulphur, most likely from the furnace fuel.

28 An overview of the relevant European and US standards can be found in Chapter 1 at (Haldimann et al. 2008).

Science Selection Software CES EduPack, cast glass objects from either soda-lime or borosilicate have virtually equal strength values (Table 2.7) compared to float elements of the same glass composition (Granta Design Limited 2015).

TABLE 2.7 Strength values of standardized float/cast soda-lime and borosilicate glass by CES Edupack Program (Granta Design Limited 2015).

	Symbol	Units	Soda-lime	Borosilicate glass
Fracture tensile strength†	$f_{gl,t}$	MPa	30-35	22-32
Fracture compressive strength	$f_{gl,c}$	MPa	300-420	260-350

† *The values regarding the characteristic strength of glass can greatly vary according to the literature source used. For example, according to (O' Regan 2014) the characteristic tensile strength of soda-lime glass is 45 MPa. According to (Saint Gobain 2016; Ashby,Jones 2006; Weller et al. 2008) float soda-lime glass has a compressive strength of 1000 MPa, whereas (Oikonomopoulou et al. 2017b) has conducted experiments with borosilicate glass with a nominal compressive failure stress of 500 MPa.*

Nonetheless, in cast objects of considerably larger thickness, the manufacturing process is more difficult to control and has not been yet standardized; a current implication is the often empirical and manual production of cast glass in comparison to the mature, automated float glass production line (Bristogianni et al. 2019). Thus, the number and size of randomly distributed critical defects is anticipated to be higher[29]. In particular, the increased volume of cast glass results in more geometrical defects and inclusions in the meso-structure, such as seeds, stones and cord. Often, small air bubbles are visible by the naked eye in cast glass prototypes. A float glass containing such bubbles would have been discarded[30]. However, as the surface/edge area remains confined in dimensions, it is expected that the amount of defects at the surface or close to the edge of the cast object are marginally increased compared to float glass, mainly due to the non-standardized/non-automated production process and quality control (Fig. 2.31). Post-processing of the surface/edges of the cast elements can greatly minimize the effect of such flaws, which greatly influence

29 An extra implication is that currently a thermal or chemical tempering process has not yet been successfully developed for cast glass. This is a downside given that strengthened float glass is commonly applied in structural glass practice, and thus the cast glass product has a comparatively lower strength at the moment.

30 According to (ASTM 2008) gaseous inclusions of max. 2 mm in diameter and with a min. separation of 600 mm are allowed in a 6 mm thick float glass. For Optical Glass the standards on gaseous inclusions are considerably more strict: As an example, *SCHOTT AG* permits a 0.55 mm max. allowable diameter of a single bubble in combination with more restrictions regarding the total volume of the glass (SCHOTT Advanced Optics 2013), whereas *OHARA* allows a max. cross section of bubbles of <0.03 mm^2/100 cm^3 (Ohara 2019).

the introduction of peak stresses. Flaws in the meso-structure are considered less prevailing as long as they do not disrupt the glass network in a crucial manner. Taking the above into account, cast glass is anticipated to present a comparable yet reduced bending strength compared to standardized float glass.

In summary, casting remains a non-standardized manufacturing process for structural components in the built environment, resulting as well to a non-standardized quality. Hence, in order to avoid excessive safety factors and over-dimensioning of the components, structural applications of cast glass are currently experimentally validated.

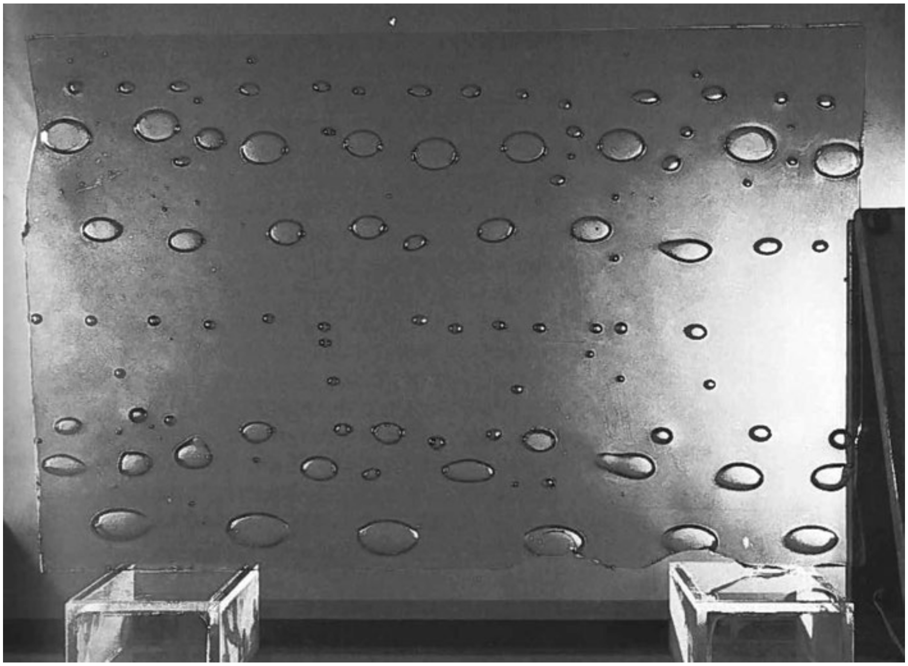

FIG. 2.31 Early piece of float glass from the *Pilkington* archive demonstrating large bubbles across the entire ribbon prior to the introduction of a fully standardized/automated process and a strict automated control of flaws and inclusions. Over the last decades, float glass has seen great developments in both infrastructure and control technology. Yet, for cast glass these aspects still remain at an earlier stage of development. Source: (Bricknell 2010)

2.7 Discussion

This chapter has sought to give an overview of the current prevailing manufacturing methods of glass, with respect to the built environment, and argue upon the potential of cast glass for building components in architectural applications.

From the presented manufacturing methods, float glass is the most prevailing one and is widely used in architecture. Nonetheless, monolithic, substantially 3-dimensional glass elements can only be achieved by 3D-printing and casting of glass. Both of these processes are relatively new for architectural applications and follow the same basic principle of molten glass being poured to form an object. The object is then controllably cooled to room temperature within an annealing kiln. Under the assumption of fully developed processes for 3D-printing and casting of glass, the former would be preferred for customized solutions and the latter for the mass fabrication of identical units. Nevertheless, the fabrication of cheap, disposable moulds can render cast glass a competitive solution for customized components as well. Overall, at present, casting provides the greatest flexibility with respect to the volume and size of the resulting glass object.

There are two main methods of casting glass: *primary casting*, which includes hot-pouring, and *secondary casting*, such as kiln-casting. The former is generally used for mass production of components while the latter is used for customized ones and requires less operating temperatures. In both processes the same annealing process is followed. The annealing schedule of an object is largely influenced by the thermal expansion coefficient of glass and the objects' thickness and mass distribution. However, more indirect factors, such as the set-up of the objects within the annealing kiln, the kiln's geometry, the type of mould, etc. further influence the annealing scheme, rendering it difficult to be accurately calculated. Thus, although several guidelines from glass manufacturers exist, the annealing schedule of large 3-dimensional objects is, in practice, still largely based on the empirical experience of the manufacturer.

A considerable obstacle in the structural application of cast glass is the lack of standardized strength data and of a standardized control process for the flaws. These exist for the float glass process but the increased volume and non-automated control of flaws in cast glass components is expected to have an effect on the strength of the resulting elements. It is anticipated though that since the mass that is comparatively increased compared to float glass is the meso-structure, the existence of critical surface flaws remains limited. Hence, the tensile strength of cast glass is anticipated to be comparable but less than that of float.

First casting attempt of the 5m in diameter borosiicate glass blank for the *Mt. Palomar Observatory*, displayed at the *Corning Museum of Glass*.

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Transparent (of a material or article)

allowing light to pass through so that objects behind can be distinctly seen.

Origin of the word transparent

Late Middle English: from Old French, from medieval Latin transparent- 'shining through', from Latin transparere, from trans- 'through' + parere 'appear'.

Definition by the Oxford Dictionary

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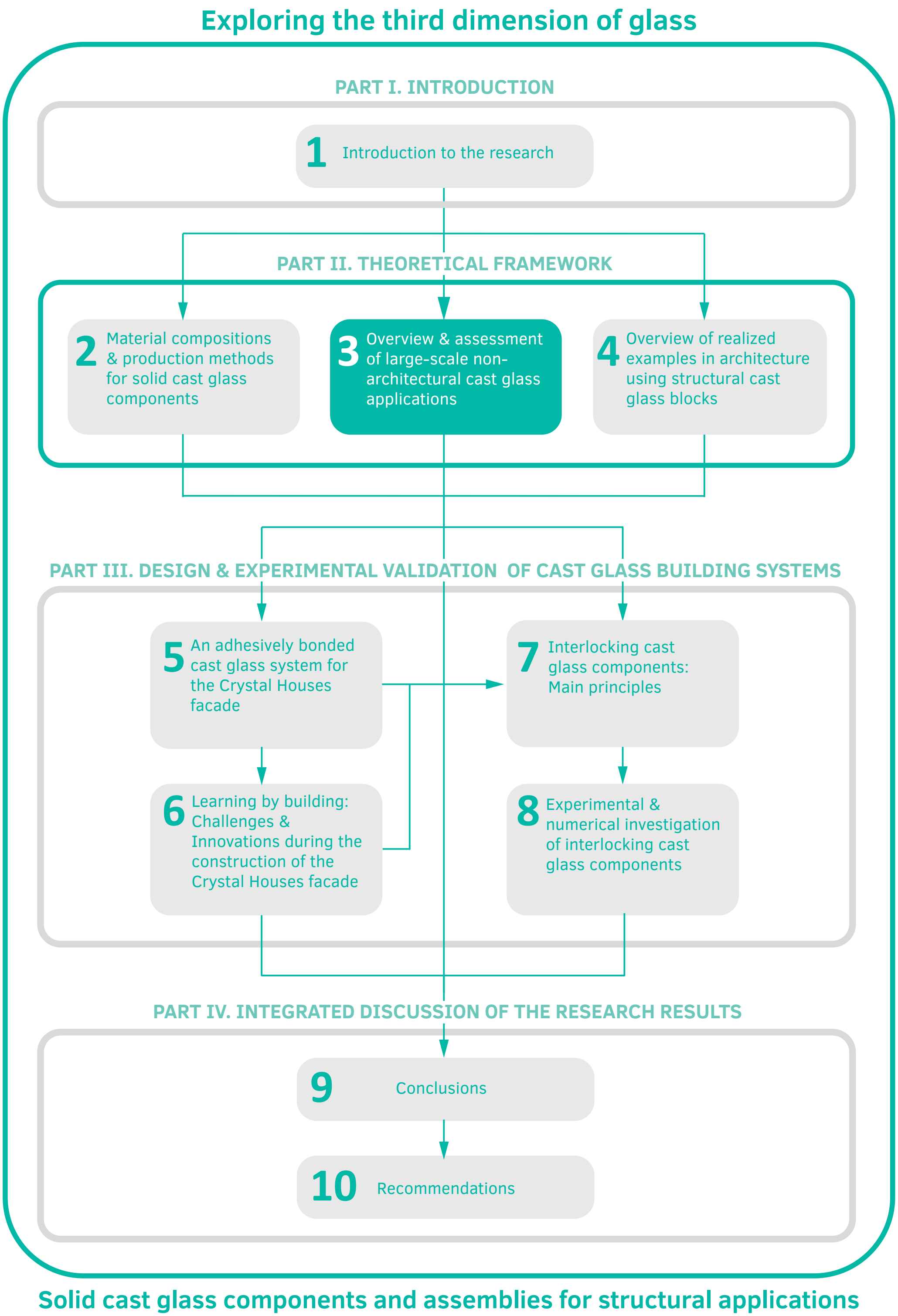
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