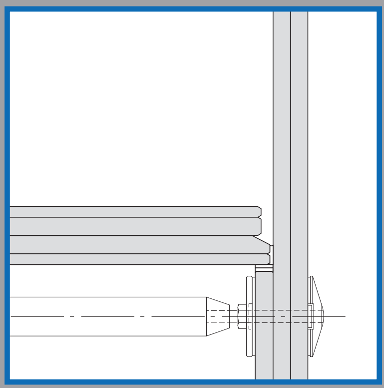
DETAIL Practice

Glass in Building

Principles
Applications
Examples



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Contents

Introduction

Building with glass

This book deals with the use of glass in building as an architectural and engineering discipline. As such, it is concerned with research into the use of glass in the building industry and its deployment in technically complex structures and assemblies that go beyond the knowledge of the glazing trade. The nature and size of these applications call for elaborate methods of calculation or special constructional solutions. In this context, glass is sometimes used not simply as an infill material; instead it is designed to carry loads that exceed the actions per unit area due to self-weight, temperature fluctuations, wind and snow. Such loads result from the diverse tasks that glass has to fulfil besides its usual function as a light-permeable enclosing material. Glass can be used to resist explosions or repel attacks, serve as a safety barrier or trafficable surface, or even function as a loadbearing component in the overall construction.
Following descriptions of the basic products, their physical features and the various processing methods (chapter 1), four further chapters explain clearly the principal relationships in the use of glass as a constructional material. The chapter "Glasses for special requirements" is followed by a chapter devoted to architectural design with respect to the optical properties of glass, the particular loadbearing and safety concepts, components and applications ("Designing with glass"). The proper forms of connection, fixing and support are the subject of the next chapter, "Constructing with glass". To enable expeditious, cost-effective and reliable planning, the chapter "Building legislation provisions" provides architects and engineers with everything they need to know about the legal side of building with glass because those applications not covered by rules or regulations may require time-consuming, costly tests. This is followed by a chapter devoted to case studies of structures already built. And finally, the appendix lists standards and sources of further information and includes a glossary to help readers understand the specialised terminology used in this book.

The importance of glass in building

Glass is a fascinating and ambivalent building material. In use, it is, on the one hand, demanding because it does not forgive any design or construction errors, but, on the other hand, indulgent when it is handled properly. When used correctly, its high demands on planning – and often also its high demands on finances – are rewarded by gains in daylight and transparency. Both aspects, i.e. our relationship with the sun and our surroundings, represent elementary human needs that are reflected in the esteem bestowed on this transparent building material. The constantly changing expression of the glass in the play of light and shade evokes stimulating sensual impressions. It is not without reason that the windows of a house are likened to the eyes of a human being.

Production of glass

The production and further development of glass, a man-made material, depends on several factors: the raw materials that form the original mix, the heat energy required to melt those raw materials, the technical conditions of a glassworks or factory, and, last but not least, highly experienced and inventive personnel. The basic composition of the raw materials mix has essentially never altered: sand, potash, or rather soda, and lime. After a method for producing soda artificially was developed in France in the late 18th century, the cost of making glass was cut considerably, which led to soda replacing potash as one of the main constituents. Up until about 1800 the enormous quantity of energy required to raise the tem-

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perature to the 1500 °C or more necessary to melt the raw materials was achieved almost exclusively with wood. But from the start of the 19th century onwards, coal was increasingly used as the energy source in regions where wood was becoming scarce, e.g. England, and later on the European continent [1].

Up until the end of the 17th century, flat glass could only be produced in a two-stage process that involved producing a hollow vessel first [2]. There were essentially two ways of doing this, which existed side by side owing to the different properties of the resulting glass products: the "blown cylinder sheet glass" and the "crown glass" processes.
In the "blown cylinder sheet glass" process a bulb of glass is blown into a cylindrical vessel with walls of minimum thickness. Once it has cooled, both ends are cut off and the cylinder is slit along its length before it is rolled flat in the flatting furnace. However, the contact with the furnace leaves blemishes on the glass surface.
The "crown glass" process exploits the centrifugal forces that ensue due to fast rotation of a blown glass bulb that is open at one point. Glass produced in this way has a fire-polished surface finish. The smaller pane dimensions possible compared to the blown cylinder sheet glass method were compensated for by the better optical quality of the finished glass product.
But the two methods described above could not satisfy the high demands that large-format mirrors had to meet. In 1688, in the light of this demand, the Frenchman Lucas de Nehou invented the casting and rolling method in which the viscous glass melt is poured onto a metal table and rolled flat [3]. But the subsequent time-consuming grinding and polishing treatment plus a coating turned the cheap cast glass into an expensive mirror.
Up until that time the raw materials were always heated in batches, but the invention of the continuous tank furnace by Friedrich Siemens in 1867, which he used in his glassworks in Dresden, marks the start of the modern age of glass melt technology [4]. At the start of the 20th century the Belgian Emile Fourcault patented his "drawing method" in which the glass is drawn continuously out of the melt vertically by means of rollers. This method provided the missing piece in the jigsaw of the industrialisation of glass production. As the glass only comes into contact with air, it has a reflective, fire-polished surface finish with a relatively high optical quality. However, the production process often leaves linear distortions in the glass. This flaw was overcome by the Englishman Alastair Pilkington, who in 1959 patented his method that still represents the state of the art in flat glass production – the "float glass method" [5]. In this process the glass melt floats on a bath of liquid tin owing to its lower density and forms a flat layer of glass of constant thickness. The horizontal, endless ribbon of glass leaving the bath of tin is of an extremely high quality (p. 12, Fig. 1).

Architecture and engineering

The development of the use of glass in building has also been affected by progress in other scientific and technical fields. The reason for this can be found in the manufacture and finishing of the glass, but also in the use of this brittle building material in conjunction with other, ductile materials. During the Gothic period, building technology had reached a point where large openings in walls were possible for the first time [6]. A fine network of iron frames formed the supporting construction for the relatively small, often coloured, translucent, diaphanous glass panes.
But the greatest technological advance was that of the Industrial Revolution. With the aid of the energy sources coal and coke, the steam engine became – literally – the driving force behind an evolution that transformed workshops into factories for producing standardised products in ever greater numbers. This process was speeded up by the fact that many inventions were both the result of and the foundation for industrialisation. Progress in science – especially exact methods for the calculation of loadbearing structures – and political changes, too, e.g. the abolition of a luxury tax on glass in England in 1851, helped to power developments in the building industry. [7]

Initially, it was not the architects who took architecture into the modern age, but rather engineers and planners from so-called non-artistic disciplines [8]. The planning of larger, purely functional, building tasks called for a vision that far exceeded that of the past and solutions whose radical expedience departed from the history of building in both aesthetic and constructional terms. The new forms of construction included sheds over railway stations in which the smoke from the locomotives could disperse, and numerous bridges with spans that had never been seen before. At the same time, the roofs to market halls, shopping arcades and other structures appeared to celebrate the symbiosis of iron and glass.

Whereas in the Gothic age glass helped to achieve the desire for brightness and colour in church interiors, in the early 19th century it was the growing popularity of exotic plants and their need for light and warmth that had a fundamental and lasting effect on architecture. Engineers optimised the building envelopes of many glasshouses, conservatories and orangeries to ensure maximum light transmittance. They were glazed from top to bot-

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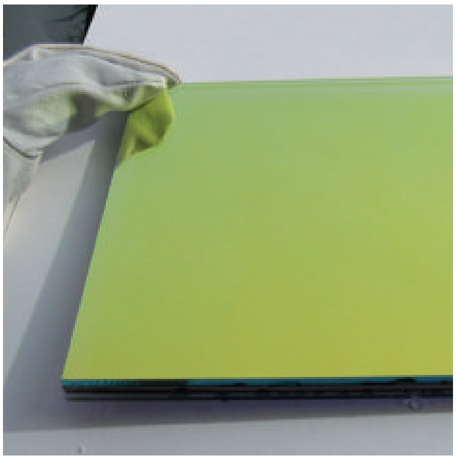
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tom; the shapes of some of them traced the trajectory of the sun across the sky so that the incidence of the sunlight on the glass was always perpendicular. The curved forms with their uniform bending radii represented a sensible compromise between the ideal structural line and the practicalities of industrial prefabrication. Glasshouses not only revolutionised architecture, they also laid the foundation stone for the use of glass as a structural element. For the first time in the history of building, panes of glass were used on a larger scale not only as an infill material but also as a stabilising component. For example, in 1827 John Claudius Loudon reported on his Palm House at Bretton Hall in Yorkshire thus: “When the ironwork was put up, before it was glazed, the slightest wind put the whole of it in motion from the base to the summit … As soon as the glass was put in, however, it was found to become perfectly firm and strong” [9]. Another fundamental concept of the modern use of glass in building was already visible in British glasshouses of that time: the mesh-like glass-and-iron constructions remained stable even if several panes were broken. The fact that many of these structures were not intended to be permanently occupied by people – therefore allowing a lower factor of safety to be assumed – had a positive effect on their design. With their widespread renunciation of historicising applications, great delicacy, overwhelming impression of transparency and use of structurally effective panes of glass (in some instances curved), the aesthetics and construction of glasshouses – in particular the Palm House at the Royal botanic Gardens in Kew near London (Fig. 1) – in some cases even exceeded those of that architectural icon of the 19th century, the Crystal Palace in London, which was designed by Joseph Paxton for the first World Exposition of 1851. At the start of the 20th century the use of glass in building experienced a new heyday, especially for industrial and office buildings, which were given large windows and glass facades. This was due to the new manufacturing and finishing methods plus an architectural development we now call the Modern Movement. The next major change came with the oil crisis of the 1970s, which forced the building industry into an energy-efficiency rethink concerning the use of glass products [10]. This resulted in systematic research into building physics relationships and led to the development of special functional glasses. The rising cost of energy together with the increasing awareness of the need for sustainable forms of construction without depleting resources have seen the rise of specialised facades since the 1980s. Their varying, frequently multilayer constructions, sometimes with controllable functional components, are intended to overcome overheating in summer and reduce energy losses in winter.

Current research is increasingly concerned with hybrid products in which several tasks are combined directly in one component. In the case of facades, for example, experiments are being carried out on curtain walls with glass photovoltaic panels, which can make an active contribution to energy needs, or passive glass loadbearing panel laminates (Figs. 2 and 3). When glass is needed only for the external protective function and transparency is not a requirement, printed or tinted glass is often an option (Fig. 4). The development of light-redirecting glass louvres exploits the optical properties of glass. On a constructional level, research is being carried out into combinations of glass and other, in some cases new, ductile materials, e.g. glass fibre-reinforced plastics. The aim here is to exploit the respective advantages of each material. In addition, plastically shaped glass is being increasingly used for architectural or structural reasons. The use of suitable adhesives with structural properties – in the automotive industry playing a part in overall stiffness since the 1970s – will also play an ever more significant role in the building industry. Therefore, progress in science and technology today and in the future will permit the design of pioneering glass projects despite ever more stringent safety requirements.

1 A masterpiece of glass-and-iron construction: the Palm House at the Royal Botanic Gardens in Kew near London (GB), 1848, Richard Turner and Decimus Burton
2 Photovoltaic panels in the cavity between the panes of an insulating glass facade (left) and individually controllable glass louvres for redirecting the light (right), Tobias Grau company building, Rellingen (D), 2001, BRT Architekten
3 Test panel of a type of dichroic glass for use as a facade element, e.g. in combination with photovoltaic panels
4 Tinted glass used on the combined police and fire station for the government district in Berlin (D), 2004, sauerbruch hutton architekten

[1] Glocker, 1992, p. 25ff.
[2] ibid., p. 76
[3] ibid., p. 80f.
[4] ibid., p.16
[5] ibid., p. 83ff.
[6] Kohlmeyer, 1998, p. 82
[7] Glocker, p. 93
[8] Baum, 2007, p. 185
[9] Loudon, 1833, p. 980
[10] Glocker, p. 94

Glass represents a special case among building materials: its transparency enables a different type of construction, which at the same time dictates a different approach because of the particular behaviour of this material. Like a diva among the building materials, glass reacts immediately and sensitively to improper treatment, which has led to its reputation as an unpredictable material. But used properly, it possesses inestimable advantages. And the treatment processes are varied and variable. So we have to know and understand glass as a material.

The material glass
In the scientific sense, the term "glass" refers to a frozen, supercooled liquid that has solidified without crystallisation. It is an amorphous substance produced by melting and rapid cooling, and hence does not have an underlying crystal lattice. This definition allows the term "glass" to stand for a multitude of substances regardless of their chemical composition. For instance, besides natural glasses, e.g. obsidian, metallic glasses or synthetic materials such as acrylic sheet can be allocated to this category.

Generally, when we speak of glass we mean the group of silicate glasses, which account for about 95 % of total glass production. These mass-produced glasses consist of about 70 % silicon dioxide, i.e. quartz sand, which during the manufacture of the glass takes on the task of the network former and determines the basic structure of the glass. As quartz sand has a very high melting point (about 1700°C), alkali oxide fluxes are mixed in to lower this. Stabilisers in the form of alkaline earth oxides form another constituent; these are added to improve the hardness and chemical resistance of the glass.

The following are among the most common silicate glasses:
• soda-lime glasses
• lead glasses
• borosilicate glasses

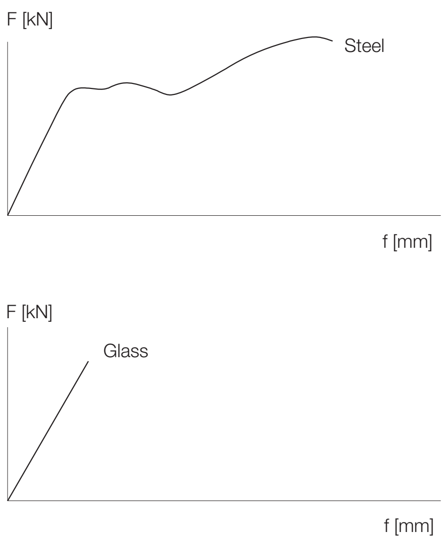
The glasses used in the building industry are in the main of the soda-lime variety. Besides the principal component, silicon dioxide, there is also a proportion of sodium oxide (Na_2O), which in the form of soda acts as a flux. Calcium oxide (CaO) functions as the stabiliser and is dissolved out of the lime that is added to the mix. In addition, there are further constituents in small amounts that depend on the particular raw materials and the processing conditions (Tab. T1). In the case of lead glass, lead oxide (PbO) replaces the calcium oxide. However, with the exception of glass for protection against x-rays, this type of glass has no significance for the building industry. Borosilicate glass – frequently used in the building industry, e.g. for fire-resistant glazing – contains a certain proportion of boron oxide (B_2O_3) instead of calcium oxide. The term alkaline earth glasses refers to a group of glass products which again have silicon dioxide as their main constituent but also contain alkaline earth oxides in varying amounts besides calcium oxide. In these glasses, potassium oxide (K_2O) replaces the sodium oxide. Alkaline earth glasses exhibit a somewhat higher density and a higher modulus of elasticity than soda-lime glass plus a lower coefficient of thermal expansion. Finally, quartz glass made from pure quartz sand also belongs to the group of silicate glasses, but plays only a minor role.

T1: Composition of soda-lime-silica glass to DIN EN 572-1

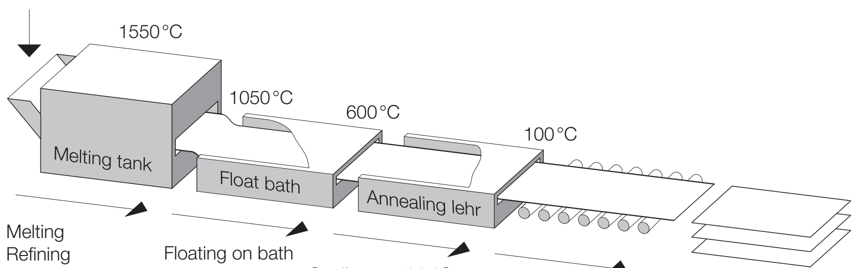
Silicon dioxide (SiO_2)	69–74 %
Calcium oxide (CaO)	5–14 %
Sodium oxide (Na_2O)	10–6 %
Magnesium oxide (MgO)	0–6 %
Aluminium oxide (Al_2O_2)	0–3 %
Others	0–5 %

The properties of glass
Two properties of glass are especially prominent and are firmly tied to this material: its transparency and its fragility.

The transparency is due to the atomic structure, i.e. its non-crystalline nature and the idiosyncrasies of the bonds within the glass itself. The lack of boundary surfaces in the material prevent the reflection of light in the range of visible and long-wave UV-A light; the atomic structure cannot absorb this light, which means that light can pass through unhindered.



1 Comparison of the mechanical behaviour of steel and glass subjected to tension (F): whereas steel exhibits plasticity after exceeding the elastic limit and is hence highly ductile (f) up until the point of failure, glass exhibits a linear elastic behaviour up to the point of failure, without any plastic material behaviour.



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On the other hand, glass is impermeable to short-wave UV-B and UV-C light because the light energy is sufficient to vibrate the electrons in the glass; this leads to the light being absorbed within the material.

Its fragility and, above all, its sudden failure characterise glass as a typical brittle material. The maximum elongation at failure is in the range of about 0.1 %. Exceeding this elastic deformability by even just a minimal amount results in sudden failure due to rupture without any “waist” forming, together with shell-shaped fracture surfaces. This means that up until this point the glass behaves in an ideal elastic fashion when subjected to mechanical actions. Plastic material behaviour does not occur, which is why it is impossible to predict failure (p. 11, Fig. 1). The high proportion of silicate in the composition of the glass is responsible for this behaviour; however, it is the silicate that gives the glass its hardness and strength. When using glass as a building material it is imperative to consider this fact at all times and to compensate for it through the use of suitable constructional measures (see “Designing with glass”, pp. 33–55, and “Constructing with glass”, pp. 57–71).

However, when talking about the tensile strength of glass we must distinguish between the theoretical tensile strength (the so-called micro-strength of the glass) and the practical tensile strength, i.e. the so-called macro-strength. The former, which can be calculated from atomic and ionic bonds in the glass structure, is very high. In the case of pure quartz glass, values between 10 000 and 30 000 N/mm^2 are possible; in the case of a mixture of raw materials, as is the case with sheet glass, 6500 to 8000 N/mm^2. In practice, however, sheet glass achieves only a fraction of this theoretical tensile strength. As with all brittle materials, in glass, too, it is the properties of the surface subjected to tension that govern the magnitude of the tensile stresses that can be accommodated. Surface flaws, notches and cracks – mostly invisible to the naked eye – ensue during manufacture and subsequent treatment and handling. When subjected to loads of any kind, stress peaks occur at these defects and the glass cannot accommodate these by way of plastic deformation, which leads to propagation of the cracks. And the longer the load is applied, the greater is the reduction in the load-carrying capacity of the glass. So brief peak loads are less of a problem for glass than lower, long-term loads. As the size of the surface area increases, so does the probability of relevant surface damage occurring at a relatively highly loaded point. So as the size of the area loaded in tension also has an influence on the tensile strength and we cannot predict with any accuracy the occurrence, nature and frequency of any surface defects, the tensile strength can only be designated in the form of a characteristic value for the material. This lies in the range 30–80 N/mm^2. In contrast to this, the compressive strength reaches very high theoretical values in practice, too. Irrespective of any surface flaws, it lies between 400 and 900 N/mm^2 for the silicate glasses normally used. As glass is both homogenous and isotropic, these and also all other properties do not depend on direction.

T2: Properties of soda-lime-silica glass to DIN EN 572-1

Density (at 18 °C)	2500 kg/m^3
Modulus of elasticity	70 000 N/mm^2
Poisson’s ratio	0.2
Average coefficient of thermal expansion	9×10^{-6} K^{-1}
Thermal fatigue resistance	40 K

Besides their good surface hardness, silicate glasses also exhibit excellent properties with respect to their resistance to chemicals and are therefore ideal where long-term durability is a requirement. Here again, the silicate basis is the reason for the good corrosion resistance. The majority of acids and alkalis cannot damage glass; one exception, however, is hydrofluoric acid, which is why this acid is used for etching glass surfaces. Glass is also highly resistant to water, but ponding on glass surfaces can lead to leaching in the long-term and hence to corrosion of the glass surface, which manifests itself in the form of cloudy patches. Glass can be damaged by industrial fumes containing ammonia and through contact with plasters/renders, wet concrete or extremely alkaline cleaning agents.

It is primarily the easy mouldability of glass that makes it suitable for use as a building material. Glass has no defined melting point at which sudden liquefying or the onset of melting occurs, as is the case with crystals. Glass is characterised by a continual softening as the temperature rises, which means that upon being heated we observe a constant transition from the brittle material via the viscoelastic range to a viscous melt. It is this property that is exploited for the workability of glass in the form of different production methods plus moulding with the help of heat. The transition range in which glass changes from a brittle to a plastic-viscous material lies between 520 and 550°C for the common, mass-produced silicate glasses.

1 Sketch of the principle of the float glass process
2 Sketch of the principle of the rolled glass process
3 Surface textures of patterned glasses (selection)