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GLASS IN STRUCTURAL APPLICATIONS

Marcin Kozłowski, PhDEng
Silesian University of Technology, Gliwice, Poland, marcin.kozlowski@polsl.pl
Andrzej Malewski, MSc Eng
University of Technology, Poznań, andrzej.n.malewski@doctorate.put.poznan.pl
Vlaho Akmadžić, PhD Eng
Faculty of Civil Engineering, University of Mostar, vlaho.akmadzic@gf.sum.ba
Anton Vrdoljak, MSc Math
Faculty of Civil Engineering, University of Mostar, anton.vrdoljak@gf.sum.ba

Abstract: Glass structures have been increasingly utilised in modern constructions for decades with load-bearing walls or facades as the most common elements. This trend can be also observed in the development of structural systems, production facilities and processing methods for glass. The article is an introduction to the topic of glass used structurally. It provides basic material properties and types of commonly used glasses. The work also reviews briefly the current standardization for glass in Europe.

Key words: structural glass, application, material properties, laminated glass, standardisation

PRIMJENA STAKLA KAO NOSIVOG ELEMENTA

Sažetak: Konstrukcije od stakla se već desetljećima sve više koriste u modernim konstrukcijama, a najčešći elementi su noseći zidovi ili fasade. Taj se trend može primijetiti i u razvoju konstruktivnih sustava, proizvodnih pogona i metoda obrade stakla. Članak je zamišljen kao uvod u temu stakla kao nosivog elementa. Navode se osnovna svojstva materijala i vrste najčešće korištenih tipova stakla. Rad također daje kratak pregled trenutno važećih standarda za staklo u Europi.

Ključne riječi: konstrukcijsko staklo, primjena, svojstva materijala, lamelirano staklo, standardizacija

1. Introduction

Glass is a material that has been widely used by architects over the last years. This is mainly due to its special features, such as translucency, high compressive strength, relatively high tensile strength, durability and resistance to environmental factors [6]. Translucent glass facades provide visual contact between building users and the external environment, which is a very important psychological factor that has a positive impact on the health and quality of life of people living and/or working in buildings. Already in 1935., the outstanding architect of the modernism period Charles-Édouard Jeanneret (LeCorbusier) in the series of his articles described glass as "the fundamental material of modern architecture" [7]. Similarly, glass has been described by Michael Wigginton as "the finest material invented by man" [22].

Nowadays, glass seems to be one of the most attractive building materials. Despite the fact that glass has been known for several thousand years, only in recent decades there has been dynamic development in the field of structural glazing[5]. Initially, glass panes were used only to fill the load-bearing window frame, usually wooden or steel. Currently, this material has become a fully responsible construction material for glass facades and load-bearing building elements, such as glass columns, beams, floor slabs and stiffening fins of facades (Figure 1).

a) b)

Figure 1. Examples of structural applications of glass: a) Load-bearing glass beams of a skylight at the train station in Eindhoven, The Netherlands, b) Load-bearing glass fins of a partition wall at the train station in Śląska, Poland(photo M. Kozłowski)

This tendency directly translates into the dynamics of the development of glass industry. According to the report "Glass and Glass Product Manufacturing – Global Markets to 2020",developed by the organization "Globe Newswire", the global market for glass and glass products in 2017 was worth $ 199.4 billion, and it is estimated that by 2020 will amount to

$ 232.4 billion. According to the 'Statistical Yearbook of Industry - 2017' published by the Central Statistical Office of Poland, the value of glass and glassware production in Poland in 2017 was amounted to PLN 11.8 billion. The current construction of two float glass facilities with a total production capacity of over 1 million tonnes per year, in conjunction with existing plants, places Poland at the forefront of glass producers in Europe, confirming the development in the field of glass production.

According to the 'Thematic BulletinTB05 – Industrial production B&H – PRODCOM result - 2017' published by the Statistical Agency of Bosnia and Herzegovina [20], the value of glass and glassware production in B&H in 2017 was amounted to BAM40.8 million.

The use of glass in construction fits in the idea of sustainable development[1]. This is due to the possibility of recycling of glass and modern technologies that allow saving energy consumed by the building, as well as the ability to harvest it. Modern glass products, such as insulated glass with special functional coatings, allow for significant energy savings by reducing the costs of heating in winter and cooling in summer [15].

Structural glass is used not only in the building industry, but it is also increasingly being used in other sectors. For example, in the automotive industry, vehicle windows are commonly made of laminated glass, which due to its high stiffness, acts as additional bracing elements, allowing for the reduction of car body weight[19]. Another example is the maritime industry, in which small flat glazing in the ship's hull is replaced in favour of large, curved laminated glass panels [10].

2. Application of glass in buildings

Soda-lime-silicate glass is commonly used in the construction industry [6]. The raw materials for its production are quartz sand, cullet and additives, most often sodium and calcium carbonate and fluxes in the form of boron oxide and lead. Currently 90% of the glass is made in so-called the float process developed by Pilkington in the 1950s in [3]. This process involves melting ground raw materials in a furnace, and then pouring the liquid mass onto a substrate of molten tin, which ensures the formation of a continuous sheet with perfectly flat surfaces [23]. In the next phase of glass production, the pane is transported on rollers to the next stage, where it is slowly cooled down to reduce thermal stress. This creates a basic glass product - the so-called annealed flat glass. The standard dimensions of the produced glass panes are 6.00 × 3.21 m, but it is possible to produce panes with a much longer length, up to 18 m [13]. Flat glass is traditionally produced with a thickness of 2 to 25 mm, while for construction applications thicknesses of 8, 10 and 12 mm are usually used.

In terms of structural behaviour, glass is significantly different from other materials widely used in construction, such as steel, reinforced concrete or wood. It is a perfectly elastic, isotropic and brittle material [6]. It has no plasticity and therefore local stress concentrations cannot be reduced by redistribution of internal forces, as it happens with e.g. steel. The biggest disadvantage of glass is its brittleness. The glass, when overloaded, breaks suddenly and without warning. Another disadvantage is the significant scatter of tensile strength of the glass and the fact that this value is not constant over time and depends on many factors, such as load duration, sample size, location of maximal stress etc. Moreover, the structural behaviour of an element made of laminated glass is highly temperature and time dependent due to the rheological nature of the interlayer used to bond the glass panes. This makes the design of glass elements complex and requires specialized knowledge and experience.

An additional difficulty is the fact that the deflection of glass panes under loading can exceed several times its thickness, which forces designers to take into account membrane stress, and thus use in the design geometric nonlinearity [6].

A key element in the design process of glass structures is to limit the concentration of stress in the glass by structural detailing and using elastic materials with low stiffness between the glass and fasteners commonly made of steel. Another aspect is to ensure the safe use of the elements in a non-cracked state, as well as in an emergency situation when the elements are fractured. Glass panes can break for various reasons, most often this happens because of their overload causing concentration of stresses leading to development of cracks well as being hit by a hard object. Thermal stress is also a common cause of fracture.

The safety of using glass elements installed in buildings can be ensured on three levels [2]. The first one is the level of material in which the type of glass used determines the load-bearing capacity of the element (e.g. the use of tempered glass increases the load-bearing capacity of the element 2-3 times). The next is the level of the element, where the use of laminated glass improves post-breakage behaviour (after fracture of a single pane, the element shows residual capacity and stiffness). Similarly, in the case of glass composites, in which the combination of glass with other materials ensures its ductile failure[11]. The last is the level of the entire structure, that should be designed in the way that the failure of a single component does not lead to a progressive catastrophe.

3. Mechanical properties of glass

Glass has a density similar to reinforced concrete (25 kN/m^3) and Young's modulus equal to aluminium (70 GPa) [6]. Despite extremely high compressive strength (approx. 1000 MPa), the glass shows much lower tensile strength, which primarily determines its suitability for structural applications[6]. The theoretical value of tensile strength is approximately 6.5-8.5 GPa, however, destructive tests show that the critical tensile stress is only a fraction of this value (30-60 MPa). The reason for such large discrepancy between the theoretical and practical glass tensile strength is that, in fact, this material shows surface defects, which is characteristic of brittle materials. For example, the surface of a glass pane has a lot of deep micro-scratches as opposed to the surface of glass fibres. The smaller the cross-section of the fibre, the fewer the material defects, and hence the higher tensile strength.

Table 1. Basic properties of soda-lime-silicate glass [6]

Property	Value
Density	2500 kg/m^3
Young's modulus	70 000 Mpa
Poisson coefficient	0.23
Characteristic tensile strength	45 Mpa
Coefficient of thermal expansion	9×10^{-6} K^{-1}
Thermal conductivity	1 W×m^{-1}K^{-1}

The tensile strength of the glass is not a constant value, it depends on many factors as the condition of the glass element surface, its size, history and duration of load, the residual stress (resulting from the glass strengthening process) and the working conditions of the elements [6]. Glass, like most construction materials, corrodes [17]. The phenomenon of matting horizontally stored glass panes in conditions of high humidity or exposed to constant contact with water is well known. Also, the natural humidity of the environment corrodes glass panes subjected to constant stress, especially if it persists for a long time. Each H_2O molecule reacts with the silicate structure of the glass to form two Si-OH groups that are not able to combine with each other and leave a gap in the silicate structure of the glass. If this reaction occurs at the tip of the crack, the gap gradually increases with atomic step and consequently, reduces the strength of glass. Large temperature changes additionally accelerate the corrosion processes. The gradual decrease in glass strength over time has been called static fatigue [17]. The basic properties of soda-lime-silicate glass are presented in Table 1.

4. Types of glass for structural applications

Three most commonly used types of glass in structural applications are annealed, thermally strengthened and tempered glass [6]. There is also chemically toughened glass available on the market (also used for mobile phone protective films). With fracture pattern being similar to annealed glass and strength comparable to toughened glass, the market share of this type of glass is negligible mainly due to the high manufacturing costs. Currently, the chemical hardening technology is mainly used for doubly-curved glass panels to which the standard heat treatment process cannot be applied.

Each type of glass has characteristic features that are key to the load-bearing capacity and safety level of the structural elements. Annealed glass is the basic product of the float process, its characteristic bending strength is 45 MPa. This type of glass is very sensitive to thermal shock and uneven heating of the pane, that can be caused by e.g. partial shading of the glass facade on a sunny day, which can lead to cracking or any kind of sticker creating spots, which absorbs more energy. The main feature of annealed glass is its perfectly flat surface, and thus this type of glass does not show optical distortions or anisotropy. Another characteristic is fracture pattern - this type of glass breaks in large pieces with sharp edges, which practically disqualifies them in applications as a monolithic pane (Figure 2a).

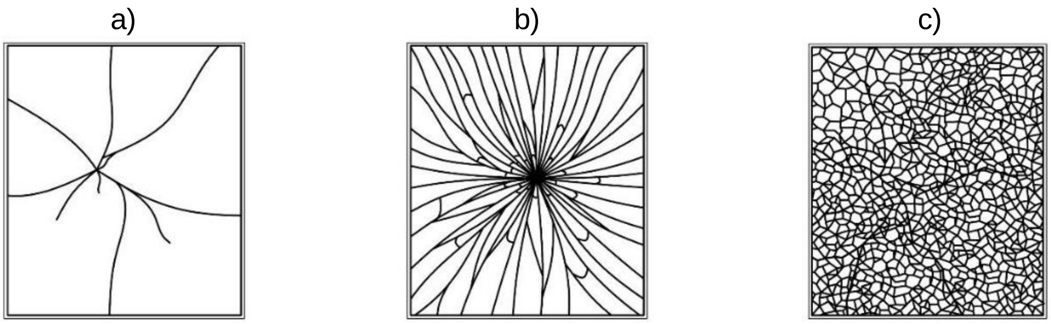

Figure 2. Comparison of fracture pattern of different types of glass: a) annealed glass, b) heat-strengthened glass, c) toughened glass [11]

The strength of annealed glass can be increased by subjecting the glass pane to heat treatment process that involves heating the pane to a temperature close to the temperature of glass transformation and quickly cooling it with a stream of cold air [6]. The result of this process is the formation of compressive surface stresses (at a thickness of about20% of the thickness of the sheet) and tensile stress in the middle of the thickness. The introduction of stress during the toughening process increases the strength of annealed glass by two to three times and increases its resistance to thermal shock and static fatigue. Depending on the stress value introduced in the thermal toughening process, two types of glass can be identified: heat-strengthened glass and toughened glass. Both types of glass are formed in the same heat treatment process, however, in case of thermally strengthened glass, the cooling rate is lower, which generates lower stress along the sheet thickness. The value of surface compressive stress for heat-strengthened glass is 40-80 MPa, while for tempered glass 80-120 MPa. Toughened glass breaks into small (dice size) pieces which significantly reduces the risk of serious injury and injury to people in its vicinity (Figure 2c). For this reason, this type of glass is commonly called safety glass. However, the name can be misleading because often an element made of tempered glass does not break down into individual fragments (dices), and often they are joined together, creating a mass that, in the event of a fall from a significant height, can cause serious injury to people below. The element made of heat-strengthened glass breaks in the form of long fragments, which is crucial to ensure the stiffness of laminated glass after failure (Figure 2b).

A characteristic feature of thermally toughened glass are optical distortions, which are a consequence of the toughening process [14]. The first type of distortion is related to the fact that during the heat-treatment process, the heated glass is transported on ceramic rollers to the tempering chamber and due to its own weight slightly sags between the rollers, which results in the formation of a wavy surface. Besides the so-called „roller waves“ phenomena this type of glass shows also other types of imperfections such as edge bow and edge lift which may potentially cause also delamination issues. The second type of distortion concerns the specific effects of opalescence that can occur under specific sunlight, and in particular in the presence of polarized light. Optical distortions are a natural feature of toughened glass and result from its production process. These phenomena should not be considered as defects, but as the natural physical properties of high-strength safety glass.

Nickel sulfide inclusions in the glass mass are one of the main disadvantages of tempered glass [9]. They arise in the production of flat glass and are responsible for its unpredictable and spontaneous cracking, i.e. without interference from external mechanical factors. The cracking is caused by the increase in inclusion volume due to the increased temperature. Often, the sheet breaks shortly after the hardening process, but the cracking due to the nickel sulfide inclusions are also observed a few years after pane production. Inclusions cannot be eliminated, but there is a way to identify defective panes. The process called thermal soaking of tempered glass involves placing a tempered glass pane inside a special chamber for a few hours and raising the glass temperature to approx. 290ºC in order to accelerate the phase transformation process of nickel sulfide. In this way, glass panes containing inclusions, break in the soaking chamber, reducing the risk of possible breakage of the sheet after its installation, e.g. on the facade of a building.

5. Laminated glass

Monolithic panes, due to their brittle behaviour after fracture, cannot be used to make structural elements. Therefore, laminated glass is widely used in construction, which is a composite system consisting of at least two glass panes bonded together by a special polymer film [6]. Lamination takes place in an autoclave at a temperature of about 140°C and a pressure of about 14 bar. Laminated glass unlike monolithic glass shows failure capacity after the glass fracture since glass fragments adhere to the interlayer and remain in place [2].

The residual resistance of laminated glass after failure depends primarily on the size of broken glass fragments, i.e. directly on the type of glass used [21]. Laminated glass elements exhibit high failure resistance when they are made of annealed or heat-strengthened glass, which break into large fragments after failure. At the same time, these elements exhibit lower load-bearing capacity and impact resistance compared to laminated glass made of toughened sheets. Laminated glass made of tempered glass is characterized by the highest load capacity, while due to the fact that this type of glass breaks in the form of small pieces, the failure resistance of such an element is negligible (Figure 3).

Horizontally installed elements in buildings such as glass roof or floor panels are most often made of heat-strengthened glass due to its post-failure stiffness. On the other hand, facades, especially point-fixed, are made of tempered glass due to stress concentrations at the holes. The choice of glass type is particularly important for glass barriers preventing users from falling out, installed on balconies or in places of difference in the height [12].

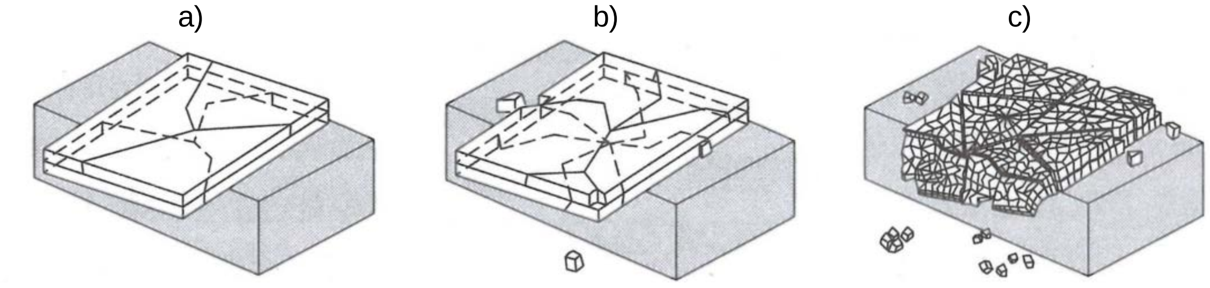

Figure 3. Post-breakage behaviour of laminated glass made of: a) annealed glass, b) heat-strenghtened glass, c) toughened glass [6]

The behaviour of laminated glass after glass failure also depends on the interlayer material [18]. The most commonly used intermediate layer is polyvinyl butyral (PVB), whose nominal thickness is 0.38 mm. Usually two or four films form one layer, 0.76 or 1.52 mm, respectively. The mechanical parameters of the film are strongly dependent on the duration of the load and temperature, and their value decrease with increasing temperature and duration of the load [4]. In case of laminated glass with PVB film, delamination often starts at the exposed edges of the element, which may result in a reduction of its load capacity.

In recent years, alternative transparent interlayer materials have been developed that are more resistant to climatic conditions, delamination and at the same time present higher rigidity, high temperature resistance, tensile strength and tear resistance. The use of a rigid film also allows to reduce the final thickness of laminated glass, which may be relevant for upgrades in existing structures.

6. Standardization for glass

The development of standards for structural glazing cannot keep up with the dynamic development of the glass industry and its needs [12]. To date, no official and harmonized standard for the design of glass components has been published in Europe [16]. Over several years, European prEN standards have been prepared, however, remained at the design stage, mainly due to a lack of unanimity among Member States. Several countries have national standards and guidelines that represent different design philosophies and are conservative to varying degrees.

In 2016, the European Committee for Standardization (CEN) established the CEN / TC 250 / SC 11 "Structural glass" committee, whose task is to develop a common glass design standard for all member countries with the working title "Eurocode 10" [8]. Ultimately, the standard will consist of three parts, regarding design basics and general principles, calculations of elements loaded perpendicular to their plane and calculations of elements loaded in the plane and analysis of connections. Individual parts of "Eurocode 10" have currently the status of drafts of technical specifications and will be the subject of consultations in the national standardization committees in the next years.

7. Conclusions

Glass is one of the most attractive construction materials known to humans, however, due to its brittleness, unpredictable behaviour after failure and the lack of harmonized design standards, it is also one of the most complex materials for structural applications. Glass design also requires specialized knowledge and numerical tools. Despite vast amount of existing glass structures, many aspects of structural design still remain unsolved, this includes exceptional loading scenarios such as fire, flood or explosions.

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