WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.155094

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 3 2025

pp. 199 – 216

Research paper

Structural aspects of using glass in facades

Marcin Kozłowski[1], Maciej Cwyl[2], Anna Jóźwik[3]

Abstract: Glass is a unique structural material that combines transparency, aesthetics and mechanical performance, making it one of the most important components in contemporary façade engineering. This paper presents a comprehensive overview of the structural use of glass in façades, with a particular focus on its mechanical properties, product types, design methodologies and system applications. The study begins with a review of the physical and chemical characteristics of float glass, including its elastic and brittle behaviour, sensitivity to surface defects and strategies for strength enhancement – such as thermal tempering and chemical strengthening. Basic glass products such as laminated glass, insulating glass units and fire-resistant glass are also discussed. A significant portion of the article is dedicated to identifying and analysing common errors that occur at different stages of façade design, construction and maintenance. Examples include issues related to thermal movement, incorrect material selection, inadequate joint detailing and insufficient maintenance strategies, all of which may compromise façade integrity and user safety. The paper also explores advanced façade systems such as unitised modules, double-skin façades, closed cavity façades and long-span glazed façades supported by trusses, cables or glass fins. Case studies of notable architectural applications, including the Markthal in Rotterdam and the Sub-Center Library in Beijing, are used to illustrate current trends and engineering challenges. Finally, the article highlights the ongoing standardization efforts in structural glass design, including the forthcoming Eurocode 10, which aims to formalize glass as a structural material within the European regulatory framework.

Keywords: design, glass facade, façade engineering, maintenance, structural glass

[1]DSc., PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: marcin.kozlowski@polsl.pl, ORCID: 0000-0002-1698-023X
[2]PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: maciej.cwyl@pw.edu.pl, ORCID: 0000-0002-2894-7840
[3]PhD., Eng., Warsaw University of Technology, Faculty of Architecture, Koszykowa 55, 00-659 Warsaw, Poland, e-mail: anna.jozwik@arch.pw.edu.pl, ORCID: 0000-0003-3252-5357

1. Introduction

Glass, due to its unique aesthetic, optical and structural properties, has become one of the fundamental materials used in contemporary construction. It is the only building material that enables the creation of transparent façades, interior partitions and load-bearing elements, thereby allowing natural daylight to penetrate deep into building interiors [1]. Notably, exposure to natural light and the ability to maintain visual contact with the surroundings have been shown to significantly influence the health and overall well-being of building occupants [2].

The primary product form is a glass pane manufactured using the float process, a method developed in the 1950s by Sir Alastair Pilkington [3]. Today, advancements in glass processing technologies allow for extensive modifications of glass in terms of performance characteristics, geometry and mechanical strength. Glass has increasingly become a subject of engineering design, driven by scientific investigations into its behaviour as a structural material. Simultaneously, numerous research and development activities are being conducted to implement innovative design solutions involving glass. These solutions are being verified through analytical, experimental and numerical approaches. Many of these studies are presented at recurring international conferences focused on the design and application of glass in architecture and engineering, such as Glass Performance Days in Tampere, Challenging Glass in Delft, Engineered Transparency in Düsseldorf, Advanced Building Skins Conference in Bern, and the Facade Tectonics World Congress (2024 – Salt Lake City).

The aim of this article is to highlight the structural and engineering nature of glass used in façades. To this end, the paper analyses and discusses the structural properties and characteristics of glass in the context of its design and application in building envelopes. Glass is a brittle material, and its failure occurs in a sudden and often unpredictable manner. This behavior distinguishes it from other, more thoroughly characterized structural materials.

2. Characteristics of glass and basic glass products

According to the definition by J.C. Maxwell, glass is a substance – regardless of its chemical composition – that, upon cooling, transitions continuously from a liquid, viscous state to a solid state, surpassing a viscosity threshold of 10^{13} dPa · s at a specific temperature [4].

The primary raw materials used in the production of soda-lime-silica glass (the most commonly used type in the construction industry) include quartz sand, cullet (recycled glass), and various additives, typically sodium carbonate and calcium carbonate. Fluxing agents such as boron oxide and lead oxide are also introduced to lower the melting temperature and modify the properties of the final product [5].

One of the most important properties of glass is its exceptional chemical resistance to a wide range of aggressive substances [6]. This characteristic makes glass widely used in the chemical industry (particularly borosilicate glass) and recognized as one of the most durable materials in construction. It is resistant to most oxidizing and non-oxidizing acids (with the exception of hydrofluoric acid), as well as to salts, hydrocarbons, alcohols, and fats. Despite its widespread use, glass is susceptible to hydrolytic corrosion, especially under the influence of moisture contained in the air [7]. This process involves the leaching of alkali ions from the glass surface, leading to its degradation. Over time, corrosion can reduce optical transparency and weaken the strength of the glass. The density of glass is comparable to that of reinforced concrete, while its Young's modulus is similar to characteristic value for aluminum. The optical properties of glass depend on its chemical composition as well as on the coatings applied to its surface. One of the greatest advantages of glass is its high transmittance of electromagnetic radiation in the visible light spectrum. Due to the presence of oxygen ions (O^{2-}) in its structure, a significant portion of ultraviolet radiation is absorbed. Infrared radiation with wavelengths exceeding 5000 nm is also blocked, as it is absorbed by Si–O groups present in the glass network [6].

Glass is an isotropic material that exhibits perfectly elastic behavior under load up to the point of failure. At the same time, similar to concrete or ceramics, it is a brittle material. This brittleness prevents the plastic redistribution of internal forces, making glass particularly sensitive to stress concentrations. Although the theoretical tensile strength of glass reaches nearly 30 GPa, the actual strength of float glass is significantly lower [8]. The characteristic tensile strength of annealed glass is only about 0.2% of the theoretical value, approximately 45 MPa [9]. This large discrepancy results from the presence of randomly distributed surface flaws, commonly referred to as Griffith microcracks, which as in other brittle materials act as stress concentrators and initiate premature failure [10].

Most surface defects in glass are invisible to the naked eye, and its strength is strongly correlated with both the number and depth of microcracks. It is important to emphasize that the strength of glass is not a fixed value but depends on numerous factors, including: the size of the element, the geometry of the critical flaw, the age of the pane, the manufacturer and processing methods [11], the location from which the element was cut out of the jumbo sheet and the type of surface (tin side vs. air side). Another category of factors contributing to the reduction of glass strength are internal (volumetric) imperfections. Even small air bubbles or inclusions of foreign materials can significantly weaken the load-bearing capacity of glass panes.

The tensile strength of glass has been extensively studied at room temperature. However, data on how this property changes with temperature are very limited and results reported by different authors are often inconsistent [12]. In general, it is assumed that the tensile strength of glass decreases with increasing temperature. Even less information is available in the literature regarding the tensile strength of glass at low temperature.

Surface flaws (microcracks) are unable to propagate under compressive loading. For this reason, the compressive strength of glass is several times higher than its tensile strength, with values reported in the literature ranging from 380 to 600 MPa [13]. However, it is important to note that compressive strength has limited practical significance from a structural design perspective. In slender glass elements subjected to compressive loads, failure typically occurs due to excessive tensile stresses, often induced by local or global buckling instability.

The fundamental concept of glass strengthening is based on inducing a non-uniform distribution of residual stresses across the glass cross-section: compressive stresses near the surfaces and balancing tensile stresses in the core of the glass [5]. The deeper layers of the glass are typically free from microcracks, which are characteristic of the surface; therefore, the tensile stresses in the core are less critical. Surface microcracks can only propagate if the compressive stresses introduced during strengthening are significantly reduced. As long as the tensile stresses resulting from external loads remain lower than the surface compressive stresses, crack propagation does not occur. In addition to increasing strength, the strengthening process significantly enhances the glass's resistance to impact and thermal shock. A non-uniform residual stress profile in the glass cross-section can be achieved by two primary methods: thermal tempering and chemical strengthening. In the thermal tempering process, depending on the treatment parameters, two types of strengthened glass can be distinguished: heat-strengthened glass and fully tempered glass with characteristic bending strength of 70 and 120 MPa, respectively [14]. The increased strength of fully tempered glass, however, comes with certain drawbacks. One of the major concerns is the presence of nickel sulphide (NiS) inclusions, which can lead to unpredictable and spontaneous breakage without any external mechanical action [15]. Such spontaneous fractures are caused by the volumetric expansion of NiS inclusions, which occurs due to temperature changes and the repeated interaction of these inclusions with the surrounding glass matrix. This leads to localized material fatigue and eventual failure. Spontaneous glass fracture is not related to the thermal tempering process, but it can be triggered due to tensile stresses in the core (introduced during this process). Another common issue associated with tempered glass is optical distortion resulting from the tempering process. In addition, an optical phenomenon known as iridescence may occur under specific lighting conditions – particularly in the presence of polarized light. In contrast to tempered glass, in which compressive surface stresses penetrate approximately 20% of the glass thickness, chemically strengthened glass exhibits a much shallower compressive stress layer, typically extending only about 100 µm from the surface. As a result, chemically strengthened glass elements are significantly more susceptible to localized surface damage.

One of the key technological processes that influence the safe use of glass in construction is lamination. The process involves connecting two or more glass panes using interlayers, most often PVB foil, which provides increased impact resistance and retains fragments upon breakage. Laminated glass is commonly used in glass structures because it shows certain level of a load-bearing capacity after destruction of the glass panes. The post fracture load capacity depends mainly on the size of the broken fragments thus the type of glass used. The highest failure load capacity after destruction is demonstrated by annealed float glass, which breaks into the largest pieces, then heat-strengthened glass and fully tempered glass [16, 17].

Standard glass panes, commonly referred to as jumbo sheets, are typically produced in dimensions of 3,210 × 6,000 mm [5]. The width of the pane is limited by the size of the glass furnace, while the length is dictated by industry standards. With the advancement of glass manufacturing technologies, it has become possible to produce significantly larger panes. The largest recorded glass pane was used in a laminated unit measuring 3,210 × 23,000 mm [18]. Flat glass is generally manufactured in thicknesses ranging from 2 to 25 mm; however, in construction applications, the most commonly used thicknesses are 4, 5, 6, 8, 10, and 12 mm.

Flat glass can also be geometrically modified through bending processes, which are categorized into hot bending and cold bending techniques [19]. Glass may be curved in one or two directions. Current technological capabilities allow the production of curved glass in large dimensions and with a wide range of curvature radii [20]. A significant challenge associated with the use of curved glass in façades is optical distortion, an undesirable effect of the thermal bending process [21].

The primary glass product used in building enclosures is insulating glass units, which consist of at least two glass panes separated by one or more spacers and hermetically sealed along the edges [6]. The space between the panes is filled with air or noble gas, which significantly improves thermal insulation and acoustic properties. In an insulating glass unit, ordinary float glass or glass with special coatings, such as solar control or low emissivity, is used. Insulating glass units, due to the tight gas-filled chambers in their structure, specifically transfer climatic loads, which affect their deflection and stresses [22, 23].

Glass in buildings is used for a variety of properties and performance characteristics. Fire-resistant glass is specifically designed to maintain integrity during a fire and, depending on its classification, may also limit heat transfer. This makes it suitable for transparent fire-rated barriers, combining safety with visual openness and architectural quality [24, 25].

3. Design, execution and maintenance errors of glass structures

The construction sector is the largest consumer of float glass, with its usage steadily increasing in parallel with the growth of building investments. The value of the global glass production market is projected to rise from USD 127 billion in 2019 to USD 175 billion by 2027 [26]. The most dynamic growth in consumption is observed in the Middle East and Africa, where flat glass is predominantly used in large-scale commercial buildings and high-rise structures. Glazing is commonly employed in both new façade constructions and the renovation of existing office buildings, where curtain walls are upgraded or replaced. In modern buildings, glass often constitutes more than 50% of the total façade surface area.

Poland is one of the leading producers and exporters of both flat glass and metal-glass façade systems in this market segment. Within Europe, Poland is among the key players responsible for supplying glass to the global market. Europe, as a whole, is the world's largest producer of glass, with over 36.8 million tons produced annually (as of 2020) [27]. Approximately 30% of this total production is flat glass intended for use in the construction industry. Consequently, glass has become one of the fundamental raw materials in modern construction, surpassing traditional façade materials such as concrete, ceramics, metal and stone cladding in terms of material usage [6, 28].

As a façade material, glass possesses specific characteristics that can lead to numerous errors and failures during the design, construction, and maintenance phases of façade systems. These failures are often costly to repair and inconvenient for investors, as they may require temporary shutdowns of entire buildings or specific areas.

At the design stage, the most common issues include incorrect assumptions in the structural schemes of metal-glass façades, failure to consider thermal effects in structural analysis [29] and the inappropriate selection of materials or profiles with insufficient stiffness to properly cooperate within the façade system. Additional problems arise from the use of unsuitable calculation methods or software, leading to incorrect assessment of the load-bearing capacity of glass panes. Glass panels must be analyzed using thin plate theory due to the high deflection-to-thickness ratios typical for these elements [30]. The Kirchhoff–Love plate theory assumes that points along a line perpendicular to the mid-surface before deformation remain on a line perpendicular to the deformed surface after bending. This assumption allows through-thickness stresses to be neglected, simplifying analysis and calculations. It is consistent with the real-world hinged support conditions often used for glass plates and enables accurate stress and deflection evaluation in the elastic state (even when deflections exceed the plate's thickness).

Design errors may also result from insufficient analysis of the primary building structure, where slab deflections and displacements of the load-bearing system adversely affect the metal-glass façade components. Other common issues include improperly selected geometries and connections at both the anchor points to the main structure and the joints between mullions and transoms of the curtain wall. Mistakes in selecting glazing based on performance criteria are also frequent [31], such as inadequate thermal insulation, local thermal bridges (dew points), or incorrect glass transparency leading to faulty light and solar radiation control.

Construction-phase errors are typically related to poor workmanship, such as improperly installed gaskets, insulators, and connectors, all of which directly affect the façade's performance and long-term durability [32]. Other issues include glass delamination, mechanical damage during transport or installation and seal failures in insulating glass units. Production-related defects may involve nickel sulphide inclusions, flaws in the glass matrix leading to unwanted reflections or transparency issues, and edge processing defects (e.g., cutting, grinding, polishing), all of which significantly impact the structural integrity and durability of the glass installed on façades.

The third group of failures pertains to the maintenance phase of metal-glass façades. As a building product, glass requires proper upkeep, including appropriate cleaning methods and chemical agents. It is sensitive to mechanical damage, especially to surface coatings that determine critical building envelope performance characteristics. The typical service life of a metal-glass façade system is approximately 25 years, during which time periodic maintenance is required. This includes gasket replacement, re-adjustment of structural joints, and servicing of sliding connections to maintain proper thermal and stress compensation within the façade elements [33].

Glass is highly sensitive to localized stress concentrations, especially near edge supports and mounting points [34]. During service, glass panels may exhibit deflections far exceeding their nominal thickness, thus necessitating periodic re-adjustment of glass fixings to prevent both air leakage and unintended contact between the glass and hard materials such as metal or stone cladding. In the maintenance phase, accurate diagnosis of façade anomalies is critical. A common error is the misidentification of the causes of even minor defects – such as localized leaks or single pane fractures – that could be repaired at low cost. Improper assessments and incorrect repair recommendations can lead to substantial expenses for the investor and further degradation of the building envelope.

An example of a design-stage error is shown in Fig. 1 [35]. The lack of proper assessment of the deformed shape of the glass plate resulted in the omission of appropriate gaskets and insufficient edge spacing between the glass pane and the metal surfaces of the transom. As a consequence of rotation at the linear support, local contact pressures and stress concentration points developed along the edge of the glass. This led to cracking and failure of the tempered glass panels in the façade.

(a) (b) (c)

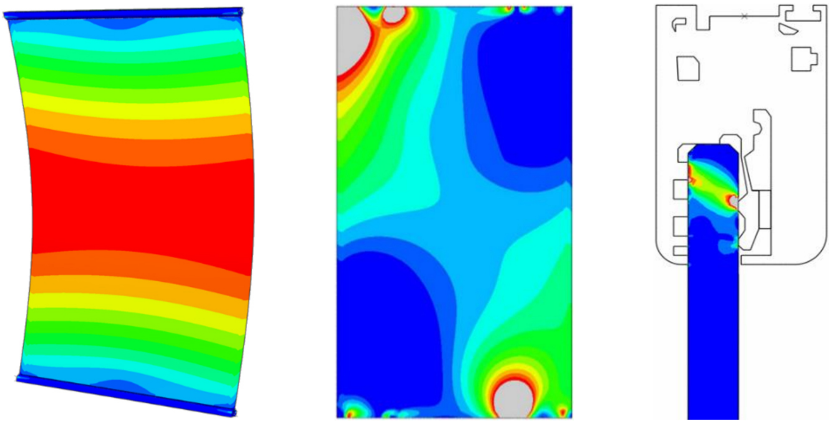

Fig. 1. Theoretical calculation model of the plate [35]: (a) faulty model not reflecting the actual stress state in the panel, (b) correct model with local stress concentration points leading to glass failure, (c) stresses not accounted for in the structural design model

An example of an error related to improper execution of a façade structure is shown in Fig. 2 (execution-stage error during on-site glazing installation). The façade system included a glass fin made of laminated, fully tempered glass, fixed and suspended at the upper node, with thermal stress compensation correctly implemented at the lower connections (a technically sound solution). However, during construction, the flooring contractor installed the floor finish tightly against the edge of the glass fin. As a result of thermal movements and wind-induced displacements, local contact occurred at the interface, leading to edge damage [17] and failure of the entire glass fin element, as shown in Fig. 2.

(a) (b) (c)

Fig. 2. Damaged glass fin resulting from an execution error: (a) general view, (b, (c) improperly spaced floor finish resulting in local contact with a glass pane (photos by M. Cwyl)

An error resulting from improper maintenance and incorrect servicing of a metal-glass façade system is presented in Fig. 3 (own research materials). The intensive development of mullion-transom metal-glass façade structures in Poland occurred between 1996 and 2005. During this period, such systems were the primary load-bearing frameworks for façades of high-rise, office and public utility buildings. Today, these structures are approximately 20 to 25 years old and in most cases require replacement, renovation, or complete refurbishment. The long-term condition of façades and glass panes has been significantly influenced by the quality of maintenance, inspection, and repair activities performed throughout the lifecycle of these systems. The defect shown in Fig. 3a resulted from a misguided expert decision to use additional screws to secure cladding strips that had begun to loosen or detach over time (originally fixed using snap-fit connections). The initial design allowed for thermal movement and proper compensation of thermal effects. However, the use of fixed screws eliminated this compensation mechanism, causing glass breakage, façade leakage, and permanent deformation of the façade mullions. This ill-advised, ad hoc intervention – intended to stabilize minor finish components – ultimately led to the need for complete reconstruction of the office building's metal-glass façade.

(a) (b) (c)

Fig. 3. Errors resulting from improper maintenance: (a) permanently deformed metal elements of the façade structure, (b) glass breakage, (c) sealant failure with local delamination (photos by M. Cwyl)

An essential aspect of the proper use and safety of façade structures is compliance with fire safety regulations. Similar to other building elements, glass façades must meet specific fire resistance classifications, typically ranging from EI 30 to EI 120, depending on the building category, fire compartment, and fire load. In Poland, these requirements are stipulated by the Regulation of the Minister of Infrastructure dated April 12, 2002, on the technical conditions to be met by buildings and their location [36], as well as the provisions of the European standard PN-EN 13501-2 [37]. Non-compliance with these fire resistance requirements is not readily apparent during the daily use of building envelopes; however, it has a significant impact on the safety of the structure and the occupants within.

4. Glass in facade engineering

Glass is widely used in façades across a variety of building types, ranging from small-scale architectural structures such as pavilions to large-scale buildings with diverse functions, including office buildings, museums, libraries, educational and research facilities, and commercial buildings. In such applications, glass is selected with particular consideration for user comfort. Key performance parameters taken into account include: total visible light transmittance (LT), total solar energy transmittance (g-value), light reflectance (LR) and thermal transmittance (U-value) [38]. For thermal insulation purposes, double- and triple-glazed insulating glass units with low-emissivity (low-E) coatings and filled with noble gases are commonly used. Due to the increasing requirements for thermal protection of the building envelope and energy efficiency of buildings, triple insulating glass units is increasingly used in new and retrofitted buildings [38–40].

Glass façades can be designed as either single-skin or double-skin systems. Among these, double-skin façades (DSF) are particularly notable for their enhanced functional performance. Their main advantages include the improvement of ventilation, airflow and thermal comfort [41], which directly contributes to the increased energy efficiency of the building envelope [42]. A typical double-skin façade consists of two layers of glass separated by a buffer zone or air cavity, typically ranging from 20 to 200 cm in width. These systems can be configured in various typologies such as box window, shaft-box, corridor and multi-storey designs [43]. A more recent solution that serves as an intermediate form between single- and double-skin façades is the Closed Cavity Façade (CCF). This system comprises a double- or triple-glazed unit (DGU or TGU) on the interior layer and a single glazing pane on the exterior, creating a sealed, non-ventilated cavity between the layers, typically from 10 to 25 cm wide, containing an automated shading device. Research has demonstrated significant advantages of CCF systems over conventional TGU solutions in terms of thermal performance and user comfort [44, 45].

From a structural perspective, glass façades are constructed using various system types, primarily including (Fig. 4) [46, 47]:

(a) (b)

Fig. 4. Aluminium glass façade system: (a) stick façade systems, Cepelia Pavilion in Warsaw, (b) unitised façade systems, 100 Bishopsgate Tower in London (photos by A. Jóźwik)

– stick façade systems,
– unitised façade systems,
– point-fixed glazing systems.

The stick system consists of vertical mullions and horizontal transoms made of aluminium, which are fixed to the main load-bearing structure of the building. The primary structural components are the mullions, which transfer loads from the transoms and the glass panels. Assembly and installation of individual system components are carried out on site, which differentiates the stick system from the unitised system. The unitised system is composed of prefabricated, repeatable modules, which integrate aluminium profiles, glazing units, insulating elements, sealants, and specially designed half-mullion and half-transom profiles (compare Fig. 5a and Fig. 5b).

(a) (b)

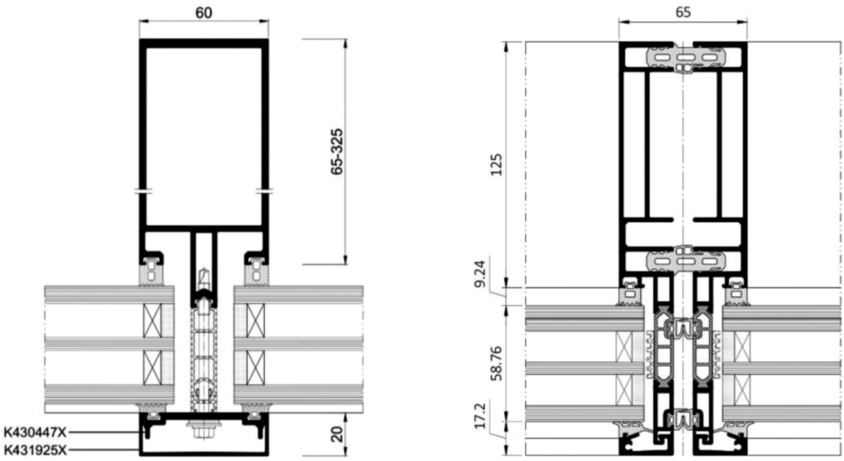

Fig. 5. Cross-section of the mullion profiles: (a) stick façade system, (b) unitized façade system (drawings of the MB-SR60N and MB-SE65 façade systems, courtesy of Aluprof)

These allow individual modules to be joined together during installation. The modules are manufactured under controlled factory conditions, improving fabrication accuracy, and are then transported and mounted to the primary building structure using brackets [48], significantly simplifying and accelerating on-site installation. Due to these advantages, unitised façades are commonly used in multi-storey and high-rise buildings.

There are design scenarios in which it becomes necessary to design and construct a façade with a height exceeding that of a typical building storey. Long-span façades, typically defined as those reaching heights of approximately 8 meters or more [49], require the use of supporting structural systems to which the glass panels are attached. These structures transfer loads to the building's primary load-bearing elements, while the glass components are verified considering self-weight, wind load, crowd load, human impact, impact from hard objects, and, in some cases, extreme loads such as seismic, blast, fire, or extreme climatic conditions [50, 51].

The selection of the appropriate supporting system depends on the façade span and significantly affects the architectural design, structural detailing, and anchoring requirements of the load-bearing elements [52]. Structural systems for tall or long-span façades can be classified as follows (Fig. 6):

– mullion-transom systems,
– mullion-only systems,
– truss-supported systems,
– cable-supported systems,
– glass fin systems,
– frameless systems with oversized glazing.

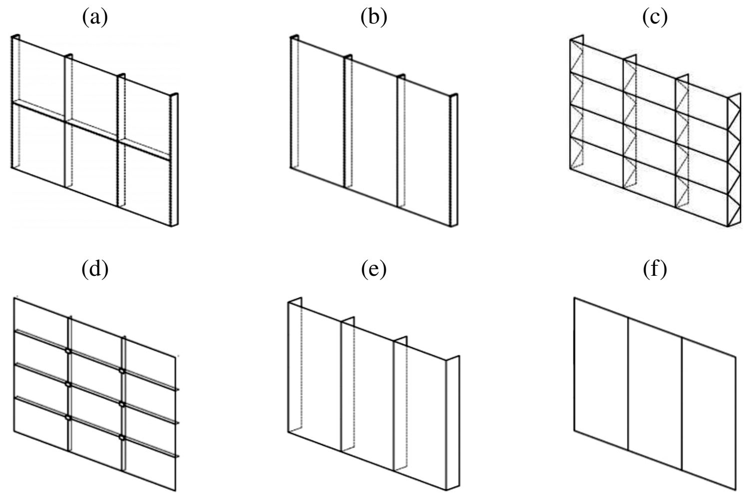

Fig. 6. Structural systems for facades: (a) mullion-transom, (b) mullion-only, (c) truss-supported, (d) cable-supported, (e) glass fin, (f) frameless with oversized glazing

From a material perspective, metal-glass façades still dominate contemporary construction. However, in recent architectural developments, there is a noticeable trend toward designing façades with an increasingly higher proportion of glass, reflecting a growing preference for transparency and minimalism in building envelopes.

In long-span façades, in addition to mullion-transom, mullion-only, and truss-supported systems, cable-supported structures are also used. These cable systems can be configured as trusses, masts, one-way mullion cables, or cable-net structures [49, 52–54]. Particularly for façades with large surface areas, cable-net systems are often employed. A prominent example of this approach is the Markthal building in Rotterdam (Fig. 7). The two large façade structures on the east and west sides each measure 35×42 meters. The cables of the cable-net system are arranged with a spacing of 1,485 mm both vertically and horizontally. Each individual glass panel is laminated, consisting of two heat-strengthened glass layers, each 6 mm thick, bonded with a 0.78 mm thick PVB interlayer. The panes are attached at all four corners

(a) (b)

Fig. 7. Cable-net glass facade in Markehall in Rotterdam, architectural project by MVRDV: (a) view from outside (©Ossip van Duivenbode), (b) view from inside (©Daria Scagliola & Stijn Brakkee)

using a circular cable-and-glass connector [55]. This type of connector is a key component in enabling point-fixed glazing in cable-supported façade systems.

The advancement of glass technologies and design methodologies for its use as a structural material has contributed to the development of fully glazed façades [28,56]. One such solution is the use of glass fin façades, where glass fins serve as vertical supports for the glass panels. Glass fins are typically composed of three layers of heat-strengthened glass, laminated together with a 1.52 mm thick PVB interlayer. In specialized applications, SentryGlas ionomer interlayer is used instead of PVB, as they offer significantly higher tensile and tear strength [57]. The spacing of glass fins depends on the modular divisions of the façade and is usually between 1.5 and 3 meters. The height of the fin may be limited by glass lamination capabilities. As a result, fins are sometimes fabricated as multi-segment elements, joined by mechanical connectors [58], although single-span glass fins are increasingly used, with panels bonded to the fins using linear silicone joints [58].

An example of a façade utilizing glass fins is the 320 South Canal tower in Chicago (Fig. 8a). The height of the glass façade in the lobby reaches 12.5 meters. The glass fins are 609 mm deep and 12,192 mm tall. Each fin consists of four layers of 12 mm heat-strengthened glass, laminated with 1.52 mm SentryGlas interlayer. The fins are spaced 3 meters apart [59].

In addition to glass fins, frameless glazing systems utilizing structural glass panels represent another design approach for fully glazed façades. In tall façades, oversized laminated glass panels are frequently employed to meet structural performance requirements.

An exemplary case of such a solution is the façade of the Sub-Center Library in Beijing (Fig. 8b). Each panel was designed as an insulating glass unit (IGU) with a total thickness of 133.6 mm and a weight of 11.5 tonnes. The flat glass panels form zigzag-shaped façade walls, each measuring 15.8 m in height and approximately 2.5 m in width. The zigzag geometry,

(a) (b)

Fig. 8. All-glass facades: (a) glass fins in skyscrapers 320 South Canal in Chicago, architectural project by Goettsch Partners (©Nick Ulivieri Photography), (b) glass panels in Sub-Center Library in Beijing, architectural project by Snøhetta (©Zhu Yumeng)

together with the substantial thickness of the panels, provides the necessary stiffness to resist wind loads. Each IGU panel consists of a laminated outer pane, made up of five layers of glass and an inner pane composed of two layers of fully tempered glass laminated with 1.52 mm thick SentryGlas Xtra ionomer interlayer. The IGU cavity, fitted with a warm-edge spacer, has a width of 20 mm. The joints between adjacent glass panels are sealed using structural silicone sealant.

5. Conclusions

Glass and metal-glass structures represent a dynamically evolving segment of the construction industry. Poland is currently the second-largest producer of flat glass in the European Union [60]. Flat glass is the primary base product, which thanks to advancements in coating technologies, has achieved increasingly improved spectrophotometric properties. A significant achievement in this regard is the thermal insulation performance of glazing systems, particularly through the reduction of thermal transmittance (U-value) in double- and triple-glazed insulating glass units with low-emission coatings, filled with noble gases such as argon or xenon [38]. Technological progress in glass production has directly fuelled the development of advanced façade systems. In large-scale building construction, including multi-storey and high-rise buildings, unitised façade systems dominate. These systems consist of prefabricated, standardized modules manufactured under factory conditions and transported to the construction site, which significantly reduces installation time and cost.

One of the most notable technological achievements in recent years has been the modification of float furnace technology, allowing for the production of glass in dimensions beyond standard formats. Moreover, tempering and lamination processes have also been adapted for oversized glass, enabling the implementation of increasingly ambitious fully glazed façades made with structural glass elements. The development of glass as a structural material is supported by numerous scientific studies. These efforts have led to the initiation of work on design standards for structural glass elements. The culmination of this process will be the publication of Eurocode 10, which is currently under development as a draft document (prEN 19100) and will significantly facilitate the structural design of glass in the future [61–64].

Façade design is inherently a multi-criteria process [65], requiring the satisfaction of diverse performance demands, ranging from usability and technical performance to structural integrity and durability. The complexity of these requirements can lead to errors not only during the design stage, but also during construction and maintenance, often resulting in damage and the need for replacement of façade components.

When designing glass façades, attention must also be paid to their service life, which is typically estimated at 20–25 years [66]. After this period, façades tend to lose their aesthetic, functional, technical, and mechanical properties, necessitating replacement or refurbishment. Today, the metal-glass façade sector has become one of the most rapidly developing and innovative segments in construction – particularly in terms of material, structural, and functional solutions. At the same time, it is important to recognize the growing share of the façade maintenance and operation segment within the broader building industry.

References

[1] M. Brzezicki, "Disturbance of transparency in the architecture of contemporary glass facades. Part 1", *Architectus*, no. 1, pp. 77–84, 2021, doi: 10.37190/arc210109.

[2] R. Kaplan, "The role of nature in the context of the workplace", *Landscape and Urban Planning*, vol. 26, no. 1–4, pp.193–201, 1993, doi: 10.1016/0169-2046(93)90016-7.

[3] M. Nascimento, "Brief history of the flat glass patent–Sixty years of the float process", *World Patent Information*, vol. 38, pp. 50–56, 2014, doi: 10.1016/j.wpi.2014.04.006.

[4] W. Vogel, Ed. *Glass chemistry*. Berlin: Springer, 1994.

[5] M. Haldimann, A. Luible, and M. Overend, *Structural use of glass*. Zurich: IABSE, 2008.

[6] M. Kosmal, A. Kuśnierz, and M. Kozłowski, *Szkło budowlane (Construction glass)*. Warsaw: PWN, 2022 (in Polish).

[7] R. Zanini, G. Franceschin, E. Cattaruzza, and A. Traviglia, "A reviewof glass corrosion: the unique contribution of studying ancient glass tovalidate glass alteration models", *Materials Degradation*, vol. 7, no. 7, pp. 1–17, 2023, doi: 10.1038/s41529-023-00355-4.

[8] S.V. Solinov, *Mechanical properties of a glass. The technology of glass: handbook*. Moscow: University of Chemical Technology of Russia, 2012.

[9] F.A. Veer and Y.M. Rodichev, "The structural strength of glass: hidden damage", *Strength of Materials*, vol. 43, pp. 302–315, 2011, doi: 10.1007/s11223-011-9298-5.

[10] A.A. Griffith, "The phenomena of rupture and flow in solids", *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, vol. 221, no. 582–593, pp. 163–198, 1921, doi: 10.1098/rsta.1921.0006.

[11] M. Cwyl and E. Modzelewska, "Analiza nośności wybranych typów tafli szklanych na podstawie badań laboratoryjnych oraz uproszczonych metod obliczeniowych", *Przegląd Budowlany*, no. 5, pp. 25–31, 2019.

[12] C. Bedon, "Structural glass systems under fire: Overview of design issues, experimental research, and developments", *Advances in Civil Engine*ering, vol. 2017, art. no. 2120570, 2017, doi: 10.1155/2017/2120570.

[13] A. Luible, "Lasteinleitungsversuche in Glaskanten", Report ICOM 463, Ecole Polytechnique Fédérale de Lausanne, 2004.

[14] EN 16612:2019 Glass in building – Determination of the lateral load resistance of glass panes by calculation. CEN, 2019.

[15] S. Karlsson, "Spontaneous fracture in thermally strengthened glass-a review and outlook", *Ceramics-Silikáty*, vol. 61, no. 3, pp. 188–201, 2017, doi: 10.13168/cs.2017.0016.

[16] M. Kozłowski, *Balustrady szklane: Analizy doświadczalne i obliczeniowe, podstawy projektowania (Glass balustrades: Experimental and numerical analysis, basis of design*). Gliwice: Wydawnictwo Politechniki Śląskiej, 2018 (in Polish).

[17] C. Bedon, M. Kozłowski, and N. Cella, "Gaps in the post-breakage out-of-plane bending stiffness assessment of 2-ply partially damaged laminated glass elements under short-term quasi-static loads", *Engineering Structures*, vol. 327, art. no. 119617, 2025, doi: 10.1016/j.engstruct.2025.119617.

[18] Morn Glass. [Online]. Available: https://www.mornglass.com/northglass-produced-23m-world-record-sgp-laminated-glass.html. [Accessed: 10 Apr. 2025].

[19] K. Datsiou, "Design and Performance of Cold Bent Glass", Ph.D. thesis, University of Cambridge, UK, 2017, doi: 10.17863/CAM.15628.

[20] H. Hohenstein, "Curved and 3D glass. The new hype in top end architecture – an examination of latest product developments and projects", in *Glass Performance Days 2019, 26–28 June 2019, Tampere, Finland*. Tampere: Glass Performance Days, 2019, pp. 1–6.

[21] N. Schlösser, "Quality control and specification for distortions of curved glass", in *Glass Performance Days 2019, 26–28 June 2019, Tampere, Finland*. Tampere: Glass Performance Days, 2019, pp. 1–6.

[22] Z. Respondek, "Influence of insulated glass units thickness and weight reduction on their functional properties", *Open Engineering*, vol. 8, no. 1, pp. 455–462, 2018, doi: 10.1515/eng-2018-0056.

[23] Z. Respondek, M. Kozłowski, and M. Wiśniowski, "Deflections and Stresses in Rectangular, Circular and Elliptical Insulating Glass Units", *Materials*, vol. 15, no. 7, art. no. 2427, 2022, doi: 10.3390/ma15072427.

[24] C. Louter, C. Bedon, M. Kozłowski, and A. Nussbaumer, "Structural response of fire-exposed laminated glass beams under sustained loads; exploratory experiments and FE-Simulations", *Fire Safety Journal*, vol. 123, art. no. 103353, 2021, doi: 10.1016/j.firesaf.2021.103353.

[25] A. Seweryn and J.M. Franssen, Comparative study of glass products used in facades and their behaviour in fire, in *4th International Symposium on Fire Safety of Facades FSF 2024, 10–12 June 2024, Lund, Sweden*, R. McNamee and J. Anderson, Eds. Lund: RISE Rapport, 2024, pp. 230–238.

[26] Office Market Pulse, „Raport z rynku biurowego lipiec-wrzesień 2023". [Online]. Available: https://www.brookfield.pl/wp-content/uploads/2023/10/OFFICE-MARKET-PULSE-III-kw.-23.pdf. [Accessed: 2 Apr. 2025].

[27] MarketHub. https://markethub.pl/tag/rynek-szkla-w-polsce/. [Accessed: 2 Apr. 2025].

[28] M. Overend, "Glass in facades and other applications", in *Structural design of buildings: Elemental design*, F. Fu and D. Richardson, Eds. Leeds: Emerald Publishing, 2024, pp. 177–212.

[29] D. Cichy, P. Drewniak, and M. Cwyl, "Wpływ oddziaływań termicznych na fasady metalowo-szklane (Impact of thermal actions on metal-glass facades)", *Świat Szkła*, no. 7/8, pp. 16–19, 2017 (in Polish).

[30] G. Jemielita, "Metoda dystrybucyjna znajdywania ugięć płyt prostokątnych dowolnie obciążonych (Distributive method for finding deflections of arbitrarily loaded rectangular plates)", *Archiwum Inżynierii Lądowej*, vol. 20, no. 1, pp. 35–46, 1974 (in Polish). Compare: *Bulletin of the Polish Academy of Sciences Technical Sciences*, vol. 20, pp. 385–391, 1972.

[31] M. Cwyl and R. Michalczyk, "Aktualne problemy badawcze metalowo-szklane struktur elewacyjnych (Current research problems of metal-glass facade structures)", *Inżynieria i Budownictwo*, vol. 77, no. 1/2, pp. 41–46, 2021 (in Polish).

[32] Z. Respondek and K. Chęciński, "Design and assembly errors in the realization of post-and-beam glass facades", *Construction of Optimized Energy Potential*, vol. 9, no. 2, pp. 71–78, 2020, doi: 10.17512/bozpe.2020.2.08.

[33] D. Honfi, A. Reith, L.G. Vigh, and G. Stocker, "Why glass structures fail?—Learning from failures of glass structures", in *Challenging Glass 4 & COST Action TU0905 Final Conference*, C. Louter, F. Bos, J. Belis, and J.-P. Lebet, Eds. Boca Raton: CRC Press, 2015, pp. 791–800.

[34] M. Kozłowski, D. Wasik, and M. Cwyl, “Experimental studies on metal-glass point connections with various configurations of mesh reinforcement”, *Archives of Civil Engineering*, vol. 70, no. 3, pp. 71–84, 2024, doi: 10.24425/ace.2024.150971.

[35] M. Cwyl, R. Michalczyk, N. Grzegorzewska, and A. Garbacz, “Predicting performance of aluminum–glass composite facade systems based on mechanical properties of the connection”, *Periodica Polytechnica Civil Engineering*, vol. 62, no. 1, pp. 259–266, 2018, doi: 10.3311/PPci.9988.

[36] Dz.U. 2002 nr 75 poz. 690 Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie.

[37] PN-EN 13501-2:2016 Fire classification of construction products and building elements – Part 2: Classification using data from fire resistance tests, excluding ventilation services. PKN, 2016.

[38] J.L. Aguilar-Santana, H. Jarimi, M. Velasco-Carrasco, and S. Riffat, “Review on window-glazing technologies and future prospects”, *International Journal of Low-Carbon Technologies*, vol. 15, no. 1, pp. 112–120, 2020, doi: 10.1093/ijlct/ctz032.

[39] M. Michael, F. Favoino, Q. Jin, A. Luna-Navarro, and M. Overend, “A Systematic Review and Classification of Glazing Technologies for Building Façades”, *Energies*, vol. 16, no. 14, art. no. 5357, 2023, doi: 10.3390/en16145357.

[40] U. Risle, “The rise of thin triple insulating glass units: An industry game-changer”. [Online]. Available: https://www.glastory.net/the-rise-of-thin-triple-insulating-glass-units/. [Accessed: 1 May 2025].

[41] A. Ghaffarianhoseini, U. Berardi, J. Tookey, D.H.W. Li, and S. Kariminia, “Exploring the advantages and challenges of double-skin facades”, *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1052–1065, 2016, doi: 10.1016/j.rser.2016.01.130.

[42] A.M. Memari, R. Solnosky, and C. Hu, “Multi-disciplinary characteristics of double-skin facades for computational modeling perspective and practical design considerations”, *Buildings*, vol. 12, no. 10, art. no. 1576, 2022, doi: 10.3390/buildings12101576.

[43] E. Oesterle, *Double-skin facades: Integrated planning*. Munich: Prestel Pub, 2001.

[44] A. Zani, C. Galante, and L. Rammig, “Thermal performance of closed cavity facades”, in *Proceedings of Façade Tectonics 2020 World Congress, 5–27 August 2020*, D. Noble, et al., Eds. Los Angeles: Tectonic Press, 2020, pp. 600–616.

[45] M. Michael and M. Overend, “Closed cavity façade, an innovative energy saving facade”, *Building Services Engineering Research and Technology*, vol. 43, no. 3, pp. 279–296, 2022, doi: 10.1177/01436244221080030.

[46] V. Di Naso, C. Ciacci, and F. Bazzocchi, “Glass facade”, in *Sustainable building development of low energy and eco-friendly constructions*, A. Krawczyk, Ed. Bialystok: Bialystok University of Technology, 2022, pp. 137–176, doi: 10.24427/978-83-67185-24-0_6.

[47] K. Kuliński and P. Palacz, “Comparison of Internal Forces Redistribution and Displacements Subjected to the Dynamic Wind Gusts depending of Point Fixed Glass Connector Model Shape”, *Periodica Polytechnica Civil Engineering*, vol. 65, no. 4, pp. 1008–1014, 2021, doi: 10.3311/PPci.18376.

[48] M. Gargallo Sanz de Vicuña, “A Systematic Approach for Unitized Curtain Walls Design”, Ph.D. thesis, Internacional Universidad Politécnica de Madrid, Madrid, Espania, 2021.

[49] M. Patterson, G.G. Schierle, M.E. Schiler, and D. Noble, “Skin and Bones: Structural System Choices for Long Span Glass Facades”, in *ACSA Annual Conference Proceedings – Association of Collegiate Schools of Architecture Conference. Houston, 27–30 March, 2008.*

[50] C. Bedon, X. Zhang, F. Santos, D. Honfi, M. Kozłowski, M. Arrigoni, L. Figuli, and D. Lange, “Performance of structural glass facades under extreme loads–Design methods, existing research, current issues and trends”, *Construction and Building Materials*, vol. 163, pp. 921–937, 2018, doi: 10.1016/j.conbuildmat.2017.12.153.

[51] W. Laufs and A. Cersosimo, “Extreme glazing load case studies: Hurricane and bomb blast”, presented at Conference GlassCon Global, Chicago, 5–7 September, 2018.

[52] M. Patterson, *Structural glass facades and enclosures*. Hoboken: John Wiley & Sons, 2011.

[53] C. Stutzki and J. Knowles, “Transparency with cable net walls”, in *Proceedings of IASS Annual Symposia, IASS 2018 Boston Symposium: Tension and membrane structures, 16–20 July 2018, Boston, USA*, Madrid: International Association for Shell and Spatial Structures (IASS), 2018, pp. 1–8.

[54] V. Komlev and J. Machacek, "Analysis of cable-net systems for glass facades", in *Proceedings of the 29th International Conference, Milovy, Czech Republic, 9–11 May, 2023*, V. Radolf and I. Zolotarev Eds. Prague: Institute of Thermomechanics of the Czech Academy of Sciences, 2023, pp. 123–126.

[55] M. Eekhout and P. van de Rotten, "Cable stayed facade in the market hall–Rotterdam", in *Challenging Glass 4 & COST Action TU0905 Final Conference*, C. Louter, F. Bos, J. Belis, and J.-P. Lebet, Eds. Boca Raton: CRC Press, 2015, pp. 577–584.

[56] A. Jóźwik, "The use of structural glass in shaping glazed facades", *Teka Komisji Urbanistyki i Architektury OddziałPAN w Krakowie*, vol. 51, pp. 359–384, 2023, doi: 10.24425/tkuia.2023.148983.

[57] A. Jóźwik, "Introduction to structural design of glass naccording to current European standards", *Archives of Civil Engineering*, vol. 68, no. 2, pp. 147–170, 2022, doi: 10.24425/ace.2022.140634.

[58] C. Bedon and M. Santarsiero, "Transparency in structural glass systems via mechanical, adhesive, and laminated connections – existing research and developments", *Advanced Engineering Materials*, vol. 20, no. 5, art. no. 1700815, pp. 1–18, 2018, doi: 10.1002/adem.201700815.

[59] A. Wagner, "320 S Canal Street |Chicago", in *Glasbau 2022*, B. Weller and T. Silke, Eds. Berlin: Ernst & Sohn, 2022, pp. 68–78.

[60] Glass For Europe. [Online]. Available: https://glassforeurope.com/the-sector/key-data/. [Accessed: 10 Apr. 2025].

[61] M. Feldmann, et al., "The new CEN/TS 19100: Design of glass structures", *Glass Structures & Engineering*, vol. 8, no. 3, pp. 317–337, 2023, doi: 10.1007/s40940-023-00219-y.

[62] prEN 19100-1:2024 Eurocode 10 – Design of glass structures – Part 1: General rules. CEN 2024.

[63] prEN 19100-2:2024 Eurocode 10 – Design of glass structures – Part 2: Out-of plane loaded glass components. CEN 2024.

[64] prEN 19100-3:2024 Eurocode 10 – Design of glass structures – Part 3: In-plane loaded glass components. CEN 2024.

[65] S. Bianchi, C. Andriotis, T. Klein, and M. Overend, "Multi-criteria design methods in facade engineering: State-of-the-art and future trends", *Building and Environment*, vol. 250, art. no. 111184, 2024, doi: 10.1016/j.buildenv.2024.111184.

[66] R. Hartwell and M. Overend, "Unlocking the re-use potential of glass facade systems", in *Glass Performance Days 2019, 26–28 June 2019, Tampere, Finland*. Tampere: Glass Performance Days, 2019, pp. 273–280.

Konstrukcyjne aspekty stosowania szkła w fasadach

Słowa kluczowe: elewacja szklana, fasada, projektowanie, szkło konstrukcyjne, utrzymanie

Streszczenie:

Szkło to unikalny materiał konstrukcyjny, który łączy w sobie przezierność, walory estetyczne oraz właściwości mechaniczne, co czyni go jednym z najważniejszych komponentów we współczesnej inżynierii fasad. Artykułprzedstawia kompleksowy przegląd zastosowania szkła jako materiału konstrukcyjnego w elewacjach, ze szczególnym uwzględnieniem jego właściwości mechanicznych, typów wyrobów, metod projektowania oraz systemów fasadowych. W pierwszej części pracy omówiono fizykochemiczne właściwości szkła float, w tym jego zachowanie sprężyste i kruche, podatność na defekty powierzchniowe oraz strategie zwiększania wytrzymałości, takie jak hartowanie termiczne i wzmacnianie chemiczne. Opisano również podstawowe wyroby szklane: szkło laminowane, zespolone oraz ognioodporne. Znaczną część artykułu poświęcono analizie typowych błędów występujących na etapie projektowania, realizacji i eksploatacji elewacji. Przykłady te obejmują problemy związane z kompensacją przemieszczeń termicznych, nieprawidłowym doborem materiałów, błędami w projektowaniu połączeń oraz niewystarczającą konserwacją – wszystkie mogą prowadzić do uszkodzeń i zagrożeń dla bezpieczeństwa użytkowników. Omówiono również zaawansowane systemy elewacyjne, takie jak moduły elementowe, fasady dwupowłokowe, systemy z zamkniętą wnęką oraz fasady wielkoformatowe wspierane przez kratownice, cięgna lub żebra szklane. Przedstawiono studia przypadków, m.in. Markthal w Rotterdamie i Sub-Center Library w Pekinie, ilustrujące aktualne trendy i wyzwania inżynierskie. Na koniec omówiono prace nad standaryzacją projektowania szkła konstrukcyjnego, w tym nadchodzącą normę Eurokod 10, która ma ułatwić projektowanie konstrukcji szklanych w Europie.

Received: 2025-05-28, Revised: 2025-06-03