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Research paper

Shaping and designing load-bearing glass walls

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Abstract: The article presents the current state of knowledge, design guidelines and principles for shaping glass load-bearing walls, which are increasingly used as structural elements in modern pavilions and public buildings. The properties of glass as a structural material are analysed, including its bending and compressive strength as well as its behaviour in a post-breakage state. Particular attention is given to glass strengthening technologies – tempering and laminating, and their impact on user safety. The article discusses the principles of designing load-bearing systems, methods of panel support, and issues related to structural stability. An analysis of fifteen pavilions from around the world that utilize glass load-bearing walls is conducted, highlighting the diversity of geometric solutions, types of glass and methods for transferring loads from the roof and wind to the supporting structure. The article also describes the draft of Eurocode 10 for the design of glass structures, which introduces consequence classes and limit state scenarios (including post-breakage phase), allowing for a comprehensive approach to the safety of load-bearing glass walls.

Keywords: designing, Eurocode 10, glass structures, load-bearing glass walls, structural glass

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1. Introduction

Glass pavilions are significant structures in the development of architectural thought. They offer opportunities for diverse design approaches, including the expression of the aesthetic qualities of the materials used and the crafting of architectural, constructional and structural detailing. This design approach can still be observed in the icon of modernism – the reconstructed pavilion designed by Mies van der Rohe for the 1929 International Exhibition in Barcelona [1]. Today, the advancement of new technologies, including glass processing, contributes to the development of innovative pavilion design solutions that incorporate glass as a structural material [2]. In this context, the load-bearing systems of glass pavilions can be shaped as spatial structures, creating fully glazed solutions such as the entrance to Buchanan Street subway station in Glasgow or the Pier Visitor Centre in Clevedon. Another approach involves systems of glass columns-ribs that carry loads from steel roofs and serve as supports for façade panels. Examples include the Apple Retail Store in Stanford and the Co-Creation Centre pavilion in Delft. A distinct group consists of pavilions in which glass walls function as load-bearing elements, transferring roof loads while also ensuring the structural stability of the system under horizontal forces such as wind action (Fig. 1).

(a) (b)

Fig. 1. Load-bearing glass walls in pavilions: (a) Crypt entrance of St Martin-in-the-Fields in London, (b) Apple retail store entrance in Milan (photo by A. Jóźwik)

Load-bearing glass walls have been the subject of intensive scientific research for over a decade, with the aim of utilizing glass not only as a material for self-supporting partitions but also as structural elements capable of carrying loads. A fundamental work in this field is the doctoral dissertation by Andreas Luible "Stability of Load-Carrying Elements in Glass" [3]. This study analyzes the load-bearing capacity and discusses possible design methods for glass elements that may fail due to instability (such as column buckling, lateral-torsional buckling and plate buckling).

Another significant contribution is the doctoral dissertation by Danijel Mocibob "Glass Panel under Shear Loading – Use of Glass Envelopes in Building Stabilization" [4]. This work focuses on the use of glass panels as structural elements that transfer loads and serve as wind bracing to stabilize and stiffen buildings.

The issue of in-plane loaded glass elements has also been addressed in the works of Bedon and Amadio [5–8], Feldmann and Langosch [9], Lenk, Weber and Dodd [10], Gwóźdź [11], Silvestru and Taras [12] and Kießlich, Engelmann, and Weller [13].

The aim of the article is to systematize the state-of-the-art on the shaping and design structures with load-bearing glass walls. The work defines engineering principles for designing the glass wall systems, based on an analysis of fifteen selected architectural case studies. It also addresses design methods for load-bearing glass walls according to the draft Eurocode 10 standard [14–18]. This paper extends the issues previously discussed in the article "Introduction to structural design of glass according to current European standards" [17] concerning the general approach to the design of structural glass. In particular, the current paper deals with the changes in the determination of bending strength of glass, as well as in the context of in-plane loaded glass elements.

2. Characteristics of glass as a structural material

Currently, the most commonly used type of glass in construction is soda-lime-silica glass, manufactured using the float process [19]. Its basic physical properties are summarized in Table [1]. The density of glass is comparable to that of reinforced concrete, while its Young's modulus is similar to that of aluminum. The optical properties of glass depend on its chemical composition and the coatings applied and one of its main advantages is its high transmittance of visible light [20, 21].

Table 1. Basic properties of soda-lime silica glass [22]

Property	**Typical numerical values and units**
Density (at 18°C)	2.5×10^3 kg/m^3
Hardness (Knoop)	6 (Mohs hardness scale)
Young's modulus	70×10^9 Pa
Poisson's ratio	0.2[1]
Specific heat capacity	0.72×10^3 J/(kg · K)
Mean linear thermal expansion coefficient (20°C to 300°C)	9×10^6
Thermal conductivity	1.0 W/m · K
Mean refractive index for visible radiation (at λ = 589.3 nm)	1.5
Emissivity (corrected)	0.837

[1] According to the standard [22], the Poisson's ratio of soda-lime silica glass is 0.20. However, design standards commonly adopt a Poisson's ratio of 0.23 [23].

Glass is a brittle material, which means it does not exhibit significant plastic deformation before failure. The characteristic strength of annealed glass is approximately 45 MPa [22]. To improve safety and increase the strength of glass, various strengthening methods are used. The most commonly employed technique is thermal tempering, which involves heating the glass to a temperature of around 620–675°C, followed by rapid cooling with air jets [19]. This process induces permanent stresses in the glass, compressive in the outer layers and tensile in the core. As a result, the strength of the glass increases by a factor of two to three.

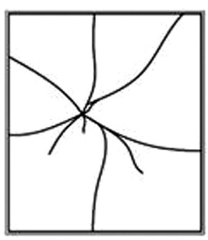
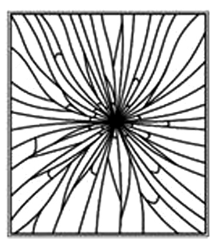
Depending on the processing parameters, thermal tempering can produce two types of strengthened glass: heat-strengthened glass and thermally toughened glass. These glass types also differ in their modes of breakage, which are influenced by the energy stored in the material's structure. This energy is the sum of residual stresses introduced during the strengthening process and the stresses caused by external loads. Table 2 presents typical modes of breakage along with the characteristic tensile strength of glass under bending [22, 24, 25].

The compressive strength of glass is several times higher than its tensile strength, with values reported in the literature typically ranging from 380 to 600 MPa [26].

One of the most important properties of glass is its exceptional chemical resistance to a wide range of aggressive substances. It is resistant to most oxidizing and non-oxidizing acids (with the exception of hydrofluoric acid), salts, hydrocarbons, alcohols and fats [21].

Another essential technique is glass lamination, which involves the permanent bonding of two or more glass panes using an interlayer. This configuration ensures the retention of glass fragments upon breakage and maintains the integrity of the partition, which is critical for both user and structural safety. The most commonly used interlayers are PVB (polyvinyl butyral) and EVA (ethylene-vinyl acetate). For special applications, high-strength interlayers such as SentryGlas are also used [27].

Table 2. Fracture pattern and characteristic strength of glass types used in construction [22, 24, 25]

	Annealed glass	**Heat-strengthened glass**	**Thermally toughened glass**
Mode of breakage			
Characteristic bending strength $f_{g,k}$ in MPa	45	70	120

3. Engineering of glass wall load-bearing systems

As stated in the introduction, one of the structural solutions used in small-scale architectural structures involves wall systems in which the main load-bearing elements are glass panels. Depending on the extent to which the wall elements contribute to the load-bearing structure, the following types of solutions can be distinguished:

– structures with the main load-bearing system composed of glass walls,
– structures designed using traditional construction technologies, where glass walls serve a structural function only in specific parts of the building.

Among the structural solutions mentioned above, freestanding pavilions with load-bearing wall systems designed entirely from glass are the most common. However, there are also buildings in which glass load-bearing walls have been designed only in specific parts of a structure constructed using conventional technologies and solutions. Such design choices are most often driven by architectural intentions, for example, to provide a view to the outside from a particular part of the building. Glass load-bearing walls can also be used in extensions to existing buildings, in which case the entire addition may be made entirely of glass.

In glass load-bearing systems, the main elements are glass panels or walls. Their arrangement should form a geometrically stable spatial-structural system to ensure [4]:

– the transfer of loads from the roof to the foundation and appropriate structural performance,
– structural stabilization,
– limitation of the system's deformations.

The design of glass load-bearing walls requires integrated connection solutions between the roof structure and the wall, as well as between the wall and the foundation, to ensure the safe transfer of loads. Since glass is a brittle material, these connections should be shaped in a way that avoids stress concentrations. Two types of glass panel connections are used: point-fixed and linear. Point-fixed connections require mechanical fasteners; however, their use involves drilling holes in the glass, which can lead to stress concentrations and potential cracking [28]. For this reason, more recent designs tend to employ connections using structural silicones. The supports themselves are typically constructed using steel shoes into which the glass panels are mounted.

A key aspect in the design of glass load-bearing walls is the limitation of their displacements. Commonly considered deformation limits range from L/100 for laminated glass walls to L/175 for DGU (double glazing unit) panels [10]. Increased deformations, particularly those caused by wind loads, have an adverse effect on the overall structural stability. Structural stabilization should be ensured in both the horizontal and vertical directions. Horizontal stabilization is achieved through structural elements and bracing components of the steel roof, or through the use of a glass panel in fully glazed pavilions. Vertical stabilization is provided by the use of glass panels. The connection between the roof and the glass panels, as well as between the panels and the foundation, should form a support system essential for stabilizing the entire structure [4].

Glass panels used in load-bearing walls are primarily designed using laminated glass, typically composed of two or three layers of heat-strengthened or thermally toughened glass. For laminating, the most commonly used interlayer is currently SentryGlas ionoplast with a thickness of 1.52 mm, due to the structural role of the walls as primary load-bearing elements (Table 3). SentryGlas ionoplast is characterized by significantly higher stiffness, tensile strength, and tear resistance compared to standard PVB films [17, 29].

Table 3. List of selected buildings with load-bearing glass walls

No.	Building name, city, date of construction, architect	Structural elements geometry		Cross-section of structural elements
		wide b, height h, radius r	thickness t	
1	Santa Fe Residence, Santa Fe (USA), 1996, arch. Studio DuBois [36, 37]	b = 1,220 mm h = 3,650 mm	t = 34.04 mm	Flat laminated glass: 6 mm + 19 mm + 6 mm (thermally toughened glass) + 2 × 1.52 mm PVB
2	Pavilion Rheinbach, Rheinbach (DE), 2002, arch. Jürgen Marquardt, Jörg Heiber [32, 33]	b = 1,270 mm h = 3,670 mm	t = 42.04 mm	Flat laminated glass: 10 mm (heat-strengthened glass) + 19 mm (thermally toughened glass) + 10 mm (heat-strengthened glass) + 2 × 1.52 mm PVB
3	Café Lichtblick 360°, Innsbruck (AT), 2005, arch. Dominique Perrault [4]	h = 3, 600 mm r = 4,675 mm	t = 21.52 mm	Bent laminated glass: 2 × 10 mm (heat-strengthened glass) + 1.52 mm PVB
4	Reception building and parking pavilion at Novartis Campus, Basel (CH), 2007, arch. Marco Serra [4, 38]	b = 1,700 mm h = 4,900 mm	t = 49.52 mm	Flat IGU + laminated glass: 8 mm (thermally toughened glass) + 16 mm cavity + 2 × 12 mm (heat-strengthened glass) + 1.52 mm PVB
			t = 39.04 mm	Glass fins: 3 × 12 mm (heat-strengthened glass) + 2 × 1.52 mm PVB
5	Crypt entrance at St Martin-in-the-Fields, London (GB), 2008, arch. Eric Parry Architects [10, 39]	h = 4,400 mm r = 3,600 mm	t = 37.04 mm	Bent laminated glass: 10 mm + 2 × 12 mm (thermally toughened glass) + 2 × 1.52 mm PVB
6	Willy-Brandt-Platz subway station, Frankfurt am Main (DE), 2010, arch. Scheffler + Partner Architekten [40]	b = 1,250 mm h = 3,070–3,500 mm	t = 39.04 mm	Flat laminated glass: 3 × 12 mm (thermally toughened glass + 2 × heat-strengthened glass) + 2 × 1.52 mm PVB
7	Kravis Center at Claremont McKenna College, Claremont (USA), 2011, arch. Rafael Viñoly Architects [40]	b = 1, 778 mm h = 3,910 mm	t = 79.60 mm	Flat laminated glass: 6 × 12 mm (thermally toughened glass) + 5 × 1.52 mm PVB

Continued on next page

Table 4. *Continued from previous page*

No.	Building name, city, date of construction, architect	Structural elements geometry		Cross-section of structural elements
		wide b, height h, radius r	thickness t	
8	Dilworth Park subway entrance, Philadelphia (USA), 2011, arch. Kieran Timberlake [41]	b = 1,500 mm h = 6,000 mm	t = 81.08 mm	Flat laminated glass: 5 × 10 mm (thermally toughened glass) + 4 × 1.52 mm SentryGlas
9	Library Walk Link, Manchester (GB), 2015, arch. SimpsonHaugh and Partners [10, 28, 34]	s = 1,858 mm h = 7,410 mm r_1 = 3,295 mm r_2 = 5,537 mm	t = 39.04 mm	Flat and bent laminated glass: 3 × 12 mm (thermally toughened glass) + 2 × 1.52 mm SentryGlas
10	Park Groot Vijversburg visitor center, Tytsjerk (NL), 2017, arch. Studio Maks and Junya Ishigami + Associates [42, 43]	h = 2,500–3,150 mm	t = 43.52 mm	Flat and bent IGU + laminated glass: 10 mm (thermally toughened glass) + 16 mm argon-filled cavity + 2 × 8 mm (heat-strengthened glass) + 1.52 mm
11	Apple Piazza Liberty, Milan (IT), 2018, arch. Foster + Partners [44]	h = 8,000 mm b = 2,500–3,000 mm	t = 52.56 mm	Flat laminated glass: 4 × 12 mm + 3 × 1.52 mm SentryGlas (thermally toughened glass)
12	Steve Jobs Theater pavilion, Cupertino (USA), 2018, arch. Foster + Partners [10, 35]	h = 6,700 mm r = 20,500 mm	t = 52.56 mm	Bent laminated glass: 4 × 12 mm (thermally toughened glass) + 3 × 1.52 mm SentryGlas
13	Museum Atelier Audemars Piguet “La Maison des Fondateurs”, Le Chenit (CH), 2020, arch. BIG [45–47]	b = 2,460 mm h = 500–5,800 mm r = 4,700–18,800 mm	t = 96.56 mm	Bent IGU + laminated glass: 2 × 8 mm (annealed float glass) + 1.52 mm SentryGlas + 16 mm argon-filled cavity + 8 mm (annealed float glass) + 16 mm argon-filled cavity + 3 × 12 mm (annealed float glass) + 2 × 1.52 mm SentryGlas
			t = 39.04 mm	Bent laminated glass: 3 × 12 mm (annealed float glass) + 2 × 1.52 mm SentryGlas
14	Pavilion Greenhouse, Opera Park, Copenhagen (DK), 2023, arch. Cobe [48]	b = 2,156 mm h = 4,150 mm r = 2,780–6,020 mm	t = 18.30 mm	Bent laminated glass: 2 × 8 mm (thermally toughened glass) + 2.28 mm SentryGlas Xtra
15	Emily Hobhouse Museum, St. Ive (GB), 2024, arch. Stonewood Design [49]	b = 20,000 mm h = 3,000 mm	t = 72.56 mm	Flat IGU + laminated glass: 2 × 8 mm + 1.52 mm SentryGlas + 16 mm cavity + 3 × 12 mm + 2 × 1.52 mm SentryGlas

Flat glass is typically used in the construction of glass pavilions, with a standard production size of 3,210 × 6,000 mm. However, with technological advancements, it is now possible to manufacture larger glass panes. To achieve thermal insulation, insulating glass units (IGUs) can be formed, consisting of a load-bearing layer and an insulating layer separated by a cavity filled with air or noble gas.

Advancements in glass technology have also enabled the production of curved glass in significantly larger dimensions and with various curvature radii [30] and also as IGUs [31]. Curved glass elements, used to modify the geometry of a structure, contribute to the spatial stiffness of the building's load-bearing system and exhibit higher load-bearing capacity [10]. For this reason, curved glass is frequently used in recent projects featuring glass load-bearing walls (Table 3).

A key aspect in shaping glass pavilions with wall-type load-bearing structures is the arrangement of the glass walls to ensure proper transmission of structural forces and overall stabilization (Fig. 2). Placing walls along the perimeter is not always sufficient, particularly in larger structures. The pavilion in Rheinbach features supports in the form of rectangular prisms arranged alternately along the longer side of the building and a steel roof (15 × 32.5 m) [32, 33]. Each prism was designed using glass panels measuring 1,270 × 3,670 mm, made of laminated glass composed of a central layer of 19 mm thick thermally toughened glass and outer layers of 10 mm thick heat-strengthened glass. The layers were bonded using a 1.52 mm thick PVB interlayer. The glass supports transfer loads from the steel roof, which has a self-weight of 28 tons.

Curved glass, combined with flat glass, was also used in the load-bearing structure of a pavilion connecting the library and town hall buildings in Manchester. The pavilion's footprint was shaped based on architectural studies aimed at harmonizing with the surrounding built environment. The structure consists of thirteen curved glass panels and thirteen flat glass panels supporting an irregularly shaped steel roof. The roof weighs approximately 27 tons [28]. The glass panels are 7.5 meters high and are composed of three 12 mm thick thermally toughened glass layers, laminated with 1.52 mm thick SentryGlas ionoplast interlayers. Overall stability is primarily ensured by shear transfer through vertical silicone joints between the panels. The roof acts as a stiff diaphragm, tying all glass panels together [34]. A key design challenge was the development of the top and bottom connections of the glass panels. A series of analyses was conducted to determine the appropriate solution [28]. The glass panels are bonded at the top and bottom to a stainless-steel shoe, which provides the structure with lateral stiffness.

Pavilions with glass load-bearing walls vary in scale. The largest example is the cylindrical pavilion that serves as the entrance to the Steve Jobs Theater in Cupertino. It has a diameter of 41 meters and a wall height of 6.7 meters. The pavilion was designed using 44 curved laminated glass panels. Each panel consists of four 12 mm thick thermally toughened glass layers bonded with 1.52 mm thick SentryGlas ionoplast interlayer. The vertical joints between panels are filled with a 30 mm thick silicone bond. The glass structure transfers loads from the roof, including the 80-ton self-weight of the carbon fiber roof [35].

Noteworthy, the Steve Jobs Theater pavilion is located in a seismically active area, which required structural solutions to withstand loads during potential earthquakes [10].

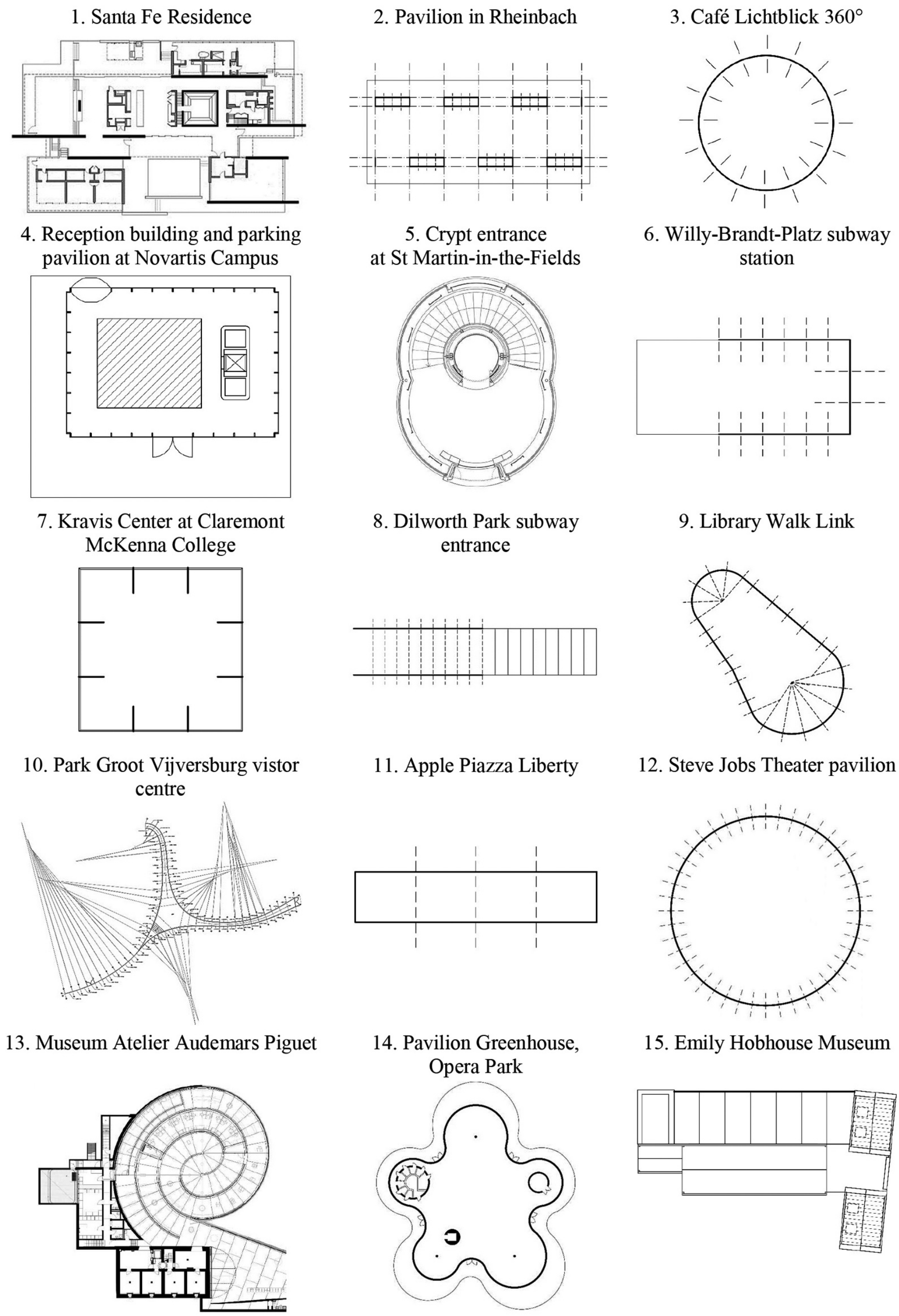


Fig. 2. Arrangement of glass load-bearing walls – plans based on architectural drawings (without scale between buildings)

4. Selected aspects of designing glass load-bearing walls

Glass is a unique structural material in terms of its mechanical and strength properties, which significantly influences its design approach. For over 20 years, analytical, experimental and numerical studies have been conducted on the strength of glass and its static performance characteristics. At the same time, efforts have been underway to develop normative documents for the design of glass structures. Currently, Eurocode 10 – Design of glass structures is in its final stage of development and currently holds the status of a draft standard, prEN 19100 [14–16].

Glass structures, due to their specific nature, require a particular approach to safety considerations. In the provisions of prEN 19100 [14–16], which is harmonized with EN 1990 [50], the concept of determining the consequence class of structural failure has been introduced for glass structures. Depending on the level of risk to human life and health, as well as the economic consequences of structural failure or loss of serviceability, consequence classes are defined and designated as CC1, CC2 or CC3. Since glass structures are typically used in selected building elements or parts (facades, roofs, vertical circulation elements, etc.), their consequence class should be determined based on the potential effects resulting from the local failure of the given element, rather than that of the entire building [51]. A different situation arises in the case of glass pavilions, where the glass walls form the primary structural system. In such cases, their failure would have serious consequences for the whole building, and therefore the consequence class may be assigned as the highest (CC3) [51–53].

The consequence classes influence the values of the partial material safety factors γ_M and γ_p used in the calculation of the design bending strength of glass $f_{g,d}$. The factor γ_M is applied to annealed (basic) glass, while γ_p is used for glass with prestressed surfaces, such as heat-strengthened glass, thermally toughened glass and chemically strengthened glass (Table 4).

Table 4. Partial factors γ_M and γ_p for glass [14]

Design situation	**Type of glass**	**Consequence class**		
		CC1	**CC2**	**CC3**
Persistent and transient (fundamental combination)	Basic material γ_M	1.6	1.8	2.0
	Surface pre-stress γ_p	1.1	1.2	1.3
Accidental	Basic material γ_M	1.0	1.1	1.2
	Surface pre-stress γ_p	1.0	1.0	1.0

As mentioned in Section 2, glass exhibits high compressive strength. However, for design purposes, the bending strength of glass $f_{g,d}$ is used, calculated according to the following formula [14] (compare to [17]):

$$f_{g,d} = \lambda_A \cdot \lambda_A \cdot k_\mathrm{e} \cdot k_\mathrm{mod} \cdot \frac{k_\mathrm{sp} \cdot f_{\mathrm{g},k}}{\gamma_M} + k_\mathrm{p} \cdot k_\mathrm{ep} \cdot \frac{f_{\mathrm{b},k} - f_{\mathrm{g},k}}{k_\mathrm{i} \cdot \gamma_\mathrm{p}} \tag{4.1}$$

where:
$f_{g,k}$ – value of characteristic bending strength of annealed glass, according to Table 1;
$f_{b,k}$ – value of characteristic bending strength of thermally or chemically strengthened glass;
λ_A – size area effect factor, for $A \leq 18$ m^2 $\lambda_A = 1.0$;
λ_l – size length effect factor, for $1 \leq$ 6 m $\lambda_l = 1.0$;
k_e – edge or hole finishing factor, for annealed float glass with polished or smooth ground edge $k_e = 1.0$;
k_{sp} – surface profile factor, for annealed float glass $k_{sp} = 1.0$;
k_p – pre-stressing process factor, for heat treatment with horizontal process $k_p = 1.0$;
k_{ep} – edge or hole pre-stressing factor, depends on the type of load (out-of-plane loading or in-plan loading), type of glass, and type of finishing edge;
k_i – is interference factor, accounting for the beneficial statistical interference between the distributions of pristine glass strengths and surface pre-stress.

Compared to the technical specifications CEN/TS 19100 [17], there have been changes in the draft standard prEN 19100 [14] for the method of determining the design bending strength of glass $f_{g,d}$. One of the key changes concerns a modification factor k_{mod}. This factor depends on the load duration t. For annealed glass, the k_{mod} factor ranges from 0.29 (for self-weight) to 1.2 for dynamic loads. For heat-strengthened, thermally toughened, and chemically strengthened glass the value of k_{mod} is taken as 1.0 (compare to [17]).

The current draft standard also introduces the interference coefficient k_i [54]. This coefficient is assigned to heat-strengthened glass and thermally toughened glass. Its value also depends on the consequence class (CC) and then its value ranges from 0.7 to 0.9. At the same time, it is the coefficient k_i that may be taken as 1.0. This approach was found to be representative of current industry practice and aligned with existing product standards [14].

According to the principles of Eurocode 10, in addition to being classified into consequence classes (CC), glass elements should also be assigned to limit state scenarios (LSS) [14]. For glass structures, beyond the standard design situations in which the structure remains intact, the cases involving partial or complete structural failure are also considered. Based on this assumption, glass elements are to be verified not only for the ultimate limit state and serviceability limit state, but also for the accidental limit state and post-failure (residual) limit state (Table 5). In the case of glass panels forming load-bearing walls, due to their critical role, it can be assumed that they should be verified in accordance with all limit state scenarios.

Table 5. Limit state scenarios (LSS) depending on limit or fracture state [14]

Design situation	**Limit state scenario (LSS)**			
	LSS-0	**LSS-1**	**LSS-2**	**LSS-3**
Design for the unfractured glass state	ULS	ULS	ULS	ULS
	SLS	SLS	SLS	SLS
Design for the glass fracture state (safe glass fracture)	–	FLS	–	FLS
Design for the post-fractured state (residual load capacity)	–	–	PLS	PLS

The verification of structural elements according to limit states is carried out based on structural analysis. In the design process of glass panels forming load-bearing walls, the following loads are taken into account: self-weight [55], crowd load [55], wind load on both the exterior and interior surfaces [56], impact loads resulting from human collision with the wall or contact with a hard object [57, 58], as well as loads related to the self-weight of the roof. The walls carry loads from the roof, which may be designed entirely of glass or made from other structural materials. Therefore, the loads transferred from the roof include its self-weight [55], wind loads [56], snow loads [59], and loads associated with maintenance activities. Glass panels located in seismically active regions are also verified for seismic loads [60]. Load combinations should be considered in accordance with EN 1990 [50].

As a result of applied loads, glass panels may be subjected to in-plane as well as out-of-plane loading. For the verification of structural behavior under normal (perpendicular to the surface) loads, Part 2 of the standard prEN 19100-2 [15] should be used. The design requirements for structural elements subjected to in-plane loading are provided in Part 3 of prEN 19100-3 [16].

In glass pavilions, in-plane loading typically results from loads transferred from the roof to the top edge of the glass panel, leading to compression of the panel. According to the provisions of prEN 19100-3 [16], elements subjected to in-plane loads must be verified with respect to:

– buckling resistance,
– glass stresses (taking into account local stress concentrations).

A significant contribution to the research on glass elements subjected to in-plane loading was made by Luible and Crisinel [3, 61–63], who conducted analytical, experimental and numerical investigations on column buckling, plate buckling, and lateral-torsional buckling. According to Luible [3], the buckling behavior of glass elements is influenced by manufacturing tolerances (such as glass thickness and geometric imperfections) as well as initial deformations.

The effects of imperfections e0 have also been addressed in prEN 19100-3 [16]:

$$e_0 = \sqrt{e^2_{0,\text{length}} + e^2_{0,\text{installation}}} \tag{4.2}$$

where :
$e_{0,\text{length}}$ – considering all imperfections of the component being length related,
$e_{0,\text{length}} = l_0/333$, l_0– component length,
$e_{0,\text{installation}}$ – considering deviations coming from unplanned eccentric load introduction,
$e_{0,\text{installation}} = h_e/2$, h_e – component thickness for calculation of installation eccentricity, $e_{0,\text{installation}}$ must be not smaller than 3 mm.

Imperfections in elements working in compression contribute to their deformation even under very small loads. In his analysis of buckling in compressed glass elements, Luible [3] began by considering the elastic critical force (Euler's buckling load) (Fig. 3):

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I}{L^2_{cr}} \tag{4.3}$$

and the maximum mid-span displacement, taking into account second-order effects:

$$w_{\max} = \frac{e}{\cos(L_{cr}/2\sqrt{N/N_{cr}})} + \frac{w_0}{1 - N/N_{cr}} \tag{4.4}$$

where w_0 is the initial deformation (compare to equation (4.2)) In Luible's study [3], it was demonstrated that the maximum tensile stress $\sigma_{\text{max, tensile}}$ in a compressed glass element can be determined using equations that account for second-order effects:

$$\sigma_{\text{max, tensile}} = \frac{N}{A} \pm \frac{M}{W} = \frac{N}{A} \pm \frac{N}{W}(w_{\max} + w_0 + e) \tag{4.5}$$

where N is the applied force, A is the sectional cross-section and W is the section modulus.

The buckling resistance of glass elements in compression can be verified based on the following condition:

$$\sigma_{\text{max, tensile}} \leq f_{g,d} \tag{4.6}$$

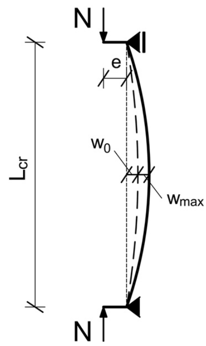


Fig. 3. Buckling model [19]

An important issue that the standard overlooks is the consideration of structural deformations due to deflection caused by wind loads, which affects the value of the critical buckling load.

The use of laminated glass is crucial for ensuring the safety of glass structures, as it provides residual post-breakage load-bearing capacity in the event of glass fracture [64, 65]. In both structural strength analysis and buckling analysis of load-bearing glass walls, the adoption of appropriate geometric parameters of the cross-section is of key importance. For laminated glass, which consists of glass plies bonded with an interlayer, an equivalent thickness (known as the effective thickness) is used [17, 18]. This value depends on the transverse shear stiffness of the interlayer, which exhibits strong rheological behavior. The shear modulus G (Kirchhoff modulus) is influenced not only by the load duration but also by temperature [66].

The accidental (fractured) state in the case of load-bearing glass walls refers to a situation in which one or more glass plies in a laminated assembly are damaged, leading to a local or global loss of the element's load-bearing capacity. Such a condition may result from random events such as impact by a soft or hard body, explosion, fire, structural overloading construction errors or vandalism.

The undamaged (residual) glass plies play a crucial role in maintaining the residual load-bearing capacity of the structure. When one of the plies fails, load redistribution occurs to the remaining undamaged components, both to the adjacent glass plies and to any supporting frames or auxiliary structural elements [67–69]. In redundant systems, it is possible to mitigate the consequences of failure and prevent the collapse of the entire structure.

A key aspect in designing such systems is the consideration of potential failure scenarios, assessment of residual capacity, and the implementation of appropriate design strategies, such as the selection of glass type, fixing method or the integration of concealed reinforcement elements.

5. Conclusions

Glass is increasingly used in architectural and engineering design because it combines aesthetic and functional features and can also be used as a structural material. One of the load-bearing structures designed with structural glass are walls. Their design requires a complex engineering approach that takes into account the material properties of glass, including its strength and brittleness. Strengthening and laminating technologies play a key role, as they affect both the load-bearing capacity of the elements and their robustness in the event of failure.

Analysis of completed projects shows that glass walls can effectively transfer both vertical and horizontal loads, provided that the connections are properly designed and the system is adequately stabilized. The wider use of glass walls as load-bearing elements is also influenced by the development of glass bending technology, as evidenced by the latest projects (Table 3). Bent glass is characterized by greater load-bearing capacity and stiffness and curved elements better stabilize the load-bearing structure.

Glass structures are designed based on numerical analyses and experimental tests. Just the introduction of normative provisions such as Eurocode 10 allows for the systematization of design principles and the assessment of the safety of glass elements under various usage scenarios, including accidental and post-failure conditions. However, the design of load-bearing elements loaded in-plane needs to be clarified. Additions including buckling curves for flexural buckling and lateral torsional buckling and their combinations for simple load cases and simple glazing aspect formats are already expected [18].

As indicated in the article, structures incorporating load-bearing glass walls have great development potential, but they require further research and refinement of design guidelines, especially in the context of complex service conditions.

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Kształtowanie i projektowanie szklanych ścian nośnych

Słowa kluczowe: Eurokod 10, konstrukcje szklane, projektowanie, szklane ściany nośne, szkło konstrukcyjne

Streszczenie:

Artykułprzedstawia aktualny stan wiedzy, wytyczne projektowe oraz zasady kształtowania szklanych ścian nośnych, które coraz częściej stosowane są jako elementy konstrukcyjne w nowoczesnych pawilonach i obiektach użyteczności publicznej. Przeanalizowano właściwości szkła jako materiału konstrukcyjnego, w tym jego wytrzymałość na zginanie, ściskanie oraz charakterystykę pracy w stanie awaryjnym. Szczególną uwagę poświęconą technologiom wzmacniana szkła – hartowaniu i laminowaniu – oraz ich wpływowi na bezpieczeństwo użytkowania. W artykule omówiono zasady kształtowania ustrojów nośnych, sposoby podparcia paneli, a także zasady związane ze stabilizacją konstrukcji. Przeprowadzono analizę piętnastu pawilonów z całego świata, w których zastosowano szklane ściany nośne. Wskazano różnorodność rozwiązań geometrycznych, rodzajów szkła oraz sposobów przenoszenia obciążeń z dachu oraz wiatru działającego na płaszczyznę ścian. Opisano także projekt normy Eurokod 10 do projektowania konstrukcji szklanych, wprowadzającą klasy konsekwencji i scenariusze stan stanów granicznych (w tym poawaryjnych), co pozwala na kompleksowe podejście do projektowania szklanych ścian nośnych.

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