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.2022.140634
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVIII ISSUE 2 2022

pp. 147 –170

Review paper

Introduction to structural design of glass according to current European standards

Anna Jóźwik[1]

Abstract: Glass is a material commonly used in construction. The development of technology related to it, and the increase in knowledge concerning its mechanical and strength properties offer opportunities for glass to be applied as a structural material. The advancement in glass structures, methods for their design, as well as guidelines and standards in this fields are being developed in parallel. This article describes the main assumptions contained in the German TRxV guidelines, the series of German DIN 18008 standards, and the European EN 16612, and EN 16613 standard. Moreover, the following article presents the concept of structural glass design included in the draft pre-standard prCEN/TS 19100, which provides the basis for the formulation of the European standard Eurocode 10. According to this pre-standard, structural elements of glass will be verified in four limit states, depending on the Limit State Scenario (LSS). Apart from the classic limit states, i.e., the ultimate limit state (ULS), and the serviceability limit state (SLS), it is also assumed to introduce a fracture limit state (FLS), and post-fracture limit state (PFLS). The article also addresses the issue of laminated glass working in structural elements. Depending on the coupling between the glass panes and the polymer or ionomer interlayers, laminated glass can be divided into complete coupled or uncoupled, and can work in intermediate situations. The methods for determining the effective thickness contained in European standards and guidelines are discussed in this article.

Keywords: glass structures, structural glass, laminated glass, EN 16612, prCEN/TS 19100, Eurocode 10

[1] PhD., Eng., Warsaw University of Technology, Faculty of Architecture, Koszykowa Street 55, 00-659 Warsaw, Poland, e-mail: anna.jozwik@arch.pw.edu.pl, ORCID: 0000-0003-3252-5357

1. Introduction

Glass provides a significant construction material in contemporary architecture. The main advantage it offers stems from its capacity for transmitting daylight into the building. The transparency of glass inspires the search for new applications for the material. However, the feature also contributes to the development of new technologies. In this area, the possibility to use glass as a structural material may be seen as one of the latest achievements. The first attempts to apply glass in self-supporting elements can be found as early as in the 1950s, e.g., the Glasbau-Hahn exhibition hall in Frankfurt am Main [1]. However, significant development in glass structures has been observed over the last twenty-five years, as evidenced by the increasingly common buildings in which glass is used for structural elements. One of the significant implementations from this period is the extension of the Broadfield House Glass Museum in Kingswinford [2]. The most innovative and advanced solutions in the field of glass structures have been applied in Apple stores worldwide [3–6], such as the Apple Covent Garden store in London (Fig. 1a).

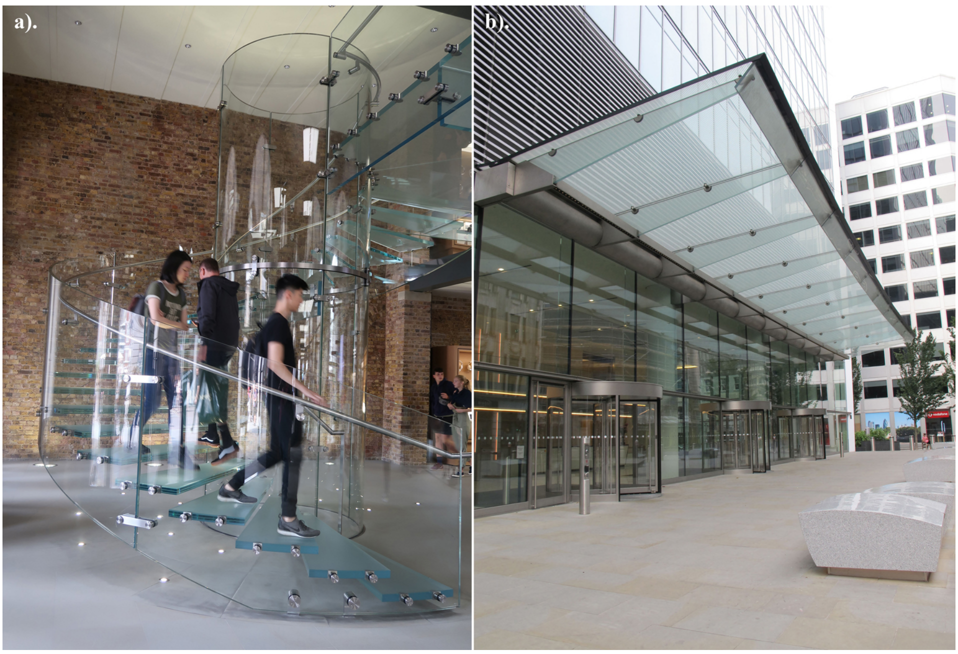


Fig. 1. Glass structures in architecture: a) glass staircases in the Apple Covent Garden store in London, b) glass canopy in the 20 Fenchurch Street skyscraper in London (photos taken by the author)

It should, however, be emphasised that the scope of the use of glass as a structural material comes with certain limitations, and only applies to selected load-bearing structures. Nonetheless, the aesthetic values presented by objects where structural glass was applied have prompted further projects and implementations [7]. The undoubted advantage offered by applying structural glass is to unify the structure consisting of structural and filling elements. This can be observed in façades, e.g., glass fins at the POLIN Museum of the History of Polish Jews in Warsaw, or in the roofing, e.g., the Family Home of John Paul II Museum in Wadowice, and the glass beams in the entrance canopy of the 20 Fenchurch Street skyscraper, London (Fig. 1b).

The development of glass structures is related to the progress in glass technology, but also the advancement in knowledge on its mechanical and strength properties. Owing to the need to broaden knowledge on structural glass, a research project under the name "TU0905 – Structural Glass – Novel design methods and next generation products" was initiated in 2010–2014, as part of COST (European Cooperation in Science & Technology). Its main objectives were to develop safe design methods for glass structures, and to develop new generation products for use in these structures. The conducted research was focussed on four areas [8]: 1) predicting complex loads on glass structures; 2) material characterisation and material improvement; 3) integrated design approach incorporating risk analysis and post-fracture performance; 4) novel glass assemblies.

The use of structural glass has also contributed to the development of normative documents for its design [9]. While observing numerous implementations in which glass structural elements were applied, it can be stated that issuing guidelines and standards for the design of glass structures tends to fall behind the development of the material and its application in architecture [10]. However, the work on normative documents is currently leading to the emergence of a harmonised European standard, that is, to Eurocode 10. It is planned that the standard will be issued at the beginning of 2024 [11].

The present article is intended to overview the main assumptions that provide an introduction to glass structure design based on the currently available normative documents.

2. Glass as a structural material

2.1. Mechanical and strength properties of glass

For glass to be used as a structural material, its mechanical properties and strength parameters are crucial. Glass is a brittle material, which is the main reason why it differs from other common structural materials. Its primary disadvantage lies in the possibility of its spontaneous fracture. Moreover, as is typical of brittle materials, the destruction of glass can proceed rapidly, with no prior indication [12].

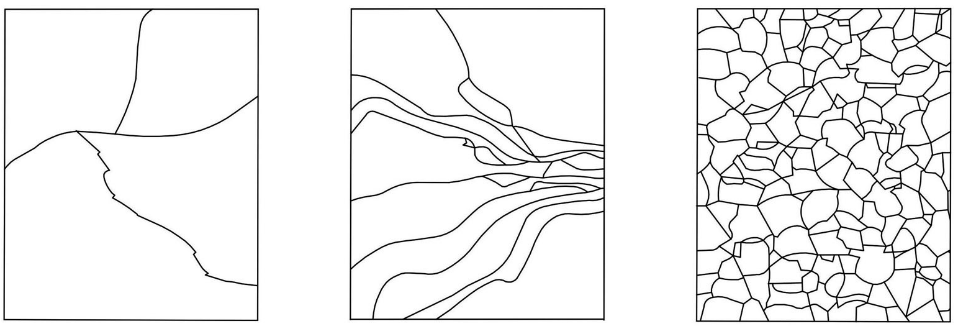
The theoretical strength of glass is very high levels and amounts to 25–30 GPa, which results from its molecular structure [12, 13]. In design applications, however, the strength parameter achieves much lower values. According to the Griffith Theory of Fracture [14], low strength values for brittle materials are caused by the occurrence of numerous cracks, which can lead to the local concentration of stresses. This, in turn, results in the glass breaking.

Glass is characterised by high values of Young's modulus, which amounts to 70,000 MPa, and is, therefore, comparable to aluminium. Its key strength is its bending strength, and in accordance with EN 572-1 [15], this is 45 MPa for annealed float glass. This value may be increased using a thermal or chemical modification process. In the case of thermal treatment, thermally toughened safety glass with a strength of 120 MPa or heat-strengthened glass with a strength of 70 MPa is obtained – as shown in Table 1. In the process of chemical treatment, a glass strength of 150 MPa may be obtained – as shown in Table 1.

Table 1. Values of characteristic bending strength $f_{g,k}$ for prestressed glass [16–18]

Modified glass / Glass product	Heat strengthened glass	Thermally toughened safety glass	Chemically strengthened glass
Float glass, drawn sheet glass	70 MPa	120 MPa	150 MPa

However, the thermal modification of glass influences the type of fracture pattern. In the event of fracture, annealed float glass is characterised by large, sharp-edged shards (Fig. 2a). In the case of thermally toughened safety glass, a fine mesh of cracks with small pieces emerges, which reduces the risk of injury (Fig. 2c). In the case of heat strengthened glass, an intermediate layout regarding sizes of glass fragments appears in the crack mesh (Fig. 2b).



annealed glass (a) — heat strengthened glass (b) — thermally toughened glass (c)

Fig. 2. Fracture pattern of different types of glass

For a higher level of safety in glass structures to be achieved, laminated glass is applied. This consists of two or more glass panes bonded with adhesive layers, such as polyvinyl butyral (PVB), ethylene-vinyl acetate (EVA), or thermoplastic polyurethane (TPU) [19]. PVB, given its thickness of 0.38, 0.76 or 1.52 mm, is the material used most often to bond glass panes. In the case of structural elements, special-purpose materials such as extra stiff PVB or SentryGlas®ionomer [20] are coming into increasingly common use.

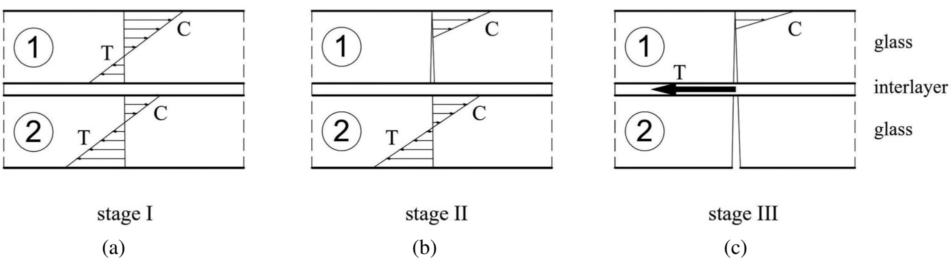
In particular, the SentryGlas®ionomer is marked with better strength parameters, including high tensile strength and five times greater tear strength than typical PVB – as shown in Table 2. It is also worth noting that the strength parameters of the interlayers applied for laminated glass bonding, including Young's relaxation modulus E and shear relaxation modulus G, depend on the load duration and the ambient temperature [23–25] – as shown in Table 2.

Table 2. Physical and strength properties of the interlayer used in laminated glass [21,22]

Properties \ Interlayer	PVB	Extra stiff PVB (Trosifol®)	Ionomer (SentryGlas®)
Density [kg/m^3]	1065	1081	950
Coefficient of linear expansion [°C^{-1}]	$2.2 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$10{\sim}15 \cdot 10^{-5}$ (−20°C÷32°C)
Tensile strength [MPa]	23	32	34.5
Tear strength (tear energy) [MJ/m^3]	10–15	–	50
Tensile elongation [%]	> 280	> 180	400
Poisson's ratio	0.5	0.5	0.5
Young's relaxation modulus $E(t)$ [MPa] 30° for 1 hour	0.97	2.7	178
Young's relaxation modulus $E(t)$ [MPa] 50° for 1 hour	0.20	1.0	12.6
Shear relaxation modulus $G(t)$ [MPa] 30° for 1 hour	0.33	0.92	60.0
Shear relaxation modulus $G(t)$ [MPa] 50° for 1 hour	0.068	0.34	4.2

2.2. Post-fracture behaviour of glass

In the case of structural glass design, its post-fracture behaviour is of great importance to ensure the safety of the entire structure [26]. Three stages of the behaviour of such glass laminates were distinguished by Kott [27]. Stage I (Fig. 3a) concerns the situation in which no glass pane fracture occurs. Thus, the distribution of compressive and tensile stresses depends on the value of the interlayer shear modulus G in the laminated glass. In stage II



stage I (a) stage II (b) stage III (c)

Fig. 3. Three stages in the failure process of laminated glass [26]

(Fig. 3b), one of the two glass panes is broken. Then, the tensile stresses at bending are taken over by the undamaged glass sheet. In the third stage (Fig. 3c), the second layer of glass is damaged. Compressive stresses can be residually borne by glass shards, while the interlayer can only counterbalance tensile stresses. Hence, properties in terms of the tear strength of the interlayers are of great importance, as high tensile elongation or tear usually leads the laminated glass being destroyed.

3. Structural glass in European standards and guidelines

The interest in possible structural glass applications led to the commencement of works on normative documents concerning methods to design glass structures [28, 29]. These documents, though often given only national status, may also be applied outside a country due to the lack of supplementary guidelines. Among the first regulations concerning the design of structural glass, the following guidelines may be mentioned: TRLV [30], TRPV [31], TRAV [32], published since 1998 by Deutsches Institut für Bautechnik (DIBt). The provisions contained in the abovementioned regulations concerned the use of glass in relatively simple and common cases. The first of the documents, i.e., the TRLV, concerned linearly supported glazing, whereas the TRAV discussed issues related to the design of protective barriers. The TRPV, in turn, presented ways to design point fixed glazing. These documents featured the key concept of glass calculation, based on the allowable stress method, with a global safety factor. A number of conditions failed to be included in the adopted method, which resulted in the design of enlarged cross-sections.

Since 2010, the guidelines published by DIBt have been systematically replaced with a national standard, i.e., DIN 18008 Glass In Building – Design and Construction Rules, with the following parts [33]:

- Part 1: Terms and general bases [34],
- Part 2: Linearly supported glazing [35],
- Part 3: Point fixed glazing [36],
- Part 4: Additional requirements for safety-barrier glazing [37],
- Part 5: Additional requirements for walk-on glazing [38],
- Part 6: Additional requirements for walk-on glazing in the case of maintenance procedures and for fall-through glazing [39],
- Part 7: Special structures (in preparation).

The DIN 18008 standard presents a different approach to the concept of safety, which is based on partial safety factors for material, geometry, loading, load and resistance side. This concept is consistent with the European construction standards: the Eurocodes. The DIN 18008 standard indicates limit states as the main method to calculate structural glass [33, 40, 41]. The verification of glazed elements consists in the examination of the ultimate limit state (ULS) and the serviceability limit state (SLS). According to its assumptions, the DIN 18008 standard was supposed to provide experience and entail the establishment of a harmonised European standard, that is, the Eurocode 10 for the design of glass structures [28, 40].

Currently, work on the Eurocode 10 is underway at the European Committee for Standardization (CEN). With this purpose in view, a special team was formed. Within the CEN/TC 250/SC 11 [42] committee named "Structural Glass", the team developed the draft pre-standard prCEN/TS 19100 on structural glass [11]. The draft pre-standard is currently being processed. It has been divided into parts [43]:

– Part 1: Basis of design and materials [44],
– Part 2: Design of out-of-plane loaded glass components [45],
– Part 3: Design of in-plane loaded components and their mechanical joints [46].

As part of this pre-standard, the classification of structural elements was proposed to facilitate the analysis of various design cases in a comparable manner. However, compared to the normative documents to date, the most significant change is related to the nature of glass as a brittle material. Two additional limit states were introduced. In addition to the traditional ultimate limit state (ULS) and serviceability limit state (SLS), the fracture limit state (FLS) and post-fracture limit state (PFLS) have been distinguished. Both of the newly introduced limit states seem of crucial importance regarding the safety of glass structures. Therefore, based on analogy to the Consequence Classes (CC) classification system contained in the EN 1990 standard [47], a division into Limit State Scenarios (LSS): LSS-0, LSS-1, LSS-2, LSS-3 was introduced, depending on the effect of the unreliability of the glass element (Table 3).

Table 3. Minimum requirements for glass components for Limit State Scenario (LSS) [43, 44]

Limit State Scenario	LSS-0a	LSS-0b	LSS-1	LSS-2	LSS-3
Examples glazing	Infill panel $A < 2\ m^2$	Infill panel larger	Balustrades; point fixed vertical glazing; glass doors	Horizontal overhead glazing; glass façades	Floors; columns; beams
Unfractured	Serviceability Limit State (SLS)				
		Ultimate Limit State (ULS)			
Fracture			Fracture Limit State (FLS)		
Post fracture				Post-fracture Limit State (PFLS I, PFLS II)	

Note: LSS-0 is out of the scope of the CEN/TS

Furthermore, it should be noted that LSS-0 is not part of EN 1990 [47] or prCEN/TS 19100-1 [44]. It is expected that the choice of the Limit State Scenario, and hence the construction design verification, will be decided at a national level. The draft pre-standard CEN/TS 19100 [44–46] on structural glass will become Eurocode 10 at the beginning of 2024 [43].

4. Basics of structural design of glass according to the 16612 and prCEN/TS 19100 standard

4.1. Assumptions according to the EN 16612 standard

According to the current European standards, the basic method for verification of structural glass is the limit state method. This design concept is also included in the EN 16612 standard [48] for lateral load resistance of linearly supported glazing used as infill panels. It is subjected to examination for two main conditions:

– determination of the maximum bending stress $\sigma_{\max}$ calculated for the most unfavourable load combinations, which cannot exceed the design value of bending strength $f_{g,d}$:

$$\sigma_{\max} \leq f_{g,d} \tag{4.1}$$

– determination of the maximum deflection $w_{\max}$ for the most unfavourable load combinations, which cannot exceed the design value of deflection w_d:

$$W_{\max} \leq W_d \tag{4.2}$$

According to the EN 16612 standard [48], an examination of the maximum bending stress in the ultimate limit state (ULS) was indicated. The essential value for verifying this condition lies in the determination of the design value of bending strength $f_{g,d}$ The EN 16612 standard [48] indicates the method to determine this strength for annealed glass and prestressed glass. The design value of bending strength for annealed glass is to be obtained using the following formula:

$$f_{g,d} = \frac{k_e \cdot k_{\text{mod}} \cdot k_{\text{sp}} \cdot f_{g,k}}{\gamma_{M,A}} \tag{4.3}$$

where:
$f_{g,d}$ – design value of the bending strength,
$f_{g,k}$ – characteristic value of the bending strength of annealed glass, $f_{g,k}$ = 45 [MPa],
$\gamma_{M,A}$ – material partial factor for annealed glass, $\gamma_{M,A} = 1.8$,
k_e – factor for edge strength,
k_{sp} – factor for the glass surface profile, for float glass $k_{\text{sp}} = 1.0$,
k_{mod} – factor for the load duration.

The design value of bending strength for prestressed glass is obtained from the following formula:

$$f_{g,d} = \frac{k_{\text{mod}} \cdot k_{\text{sp}} \cdot f_{g,k}}{\gamma_{M,A}} + \frac{k_v \left(f_{b,k} - f_{g,k}\right)}{\gamma_{M,V}} \tag{4.4}$$

where:
$f_{g,d}$ – design value of the bending strength,

$f_{g,k}$, $\gamma_{M,A}$, k_{mod}; k_{sp} – are described in formula (4.3),
$f_{b,k}$ – characteristic value of the bending for prestressed glass, accord to Table 1,
$\gamma_{M,V}$ – material partial factor for prestressed glass $\gamma_{M,V} = 1.2$,
k_V – factor for strengthening of prestressed glass, for float glass $k_V = 1.0$.

It should also be noted that in formula (4.3), the edge strength k_e factor related to the location of the stresses was distinguished. The value thereof is influenced by the glass type and by the quality of its edges. In the case that the glass is supported on its four edges, the factor value equals 1.0. However, the value may amount to less than 1.0, e.g., should the glass sheet be supported on only two of its edges.

In determining the design value of the bending strength for glass, the important element is the factor for the load duration k_{mod}, which can be obtained from the following formula:

$$k_{\text{mod}} = 0.663 \cdot t^{\frac{-1}{16}} \tag{4.5}$$

where: t – load duration in hours.

Its value is determined as a function of time (t) measured in hours; hence its value is between 0.29 and 1.0. Basic values of the k_{mod} coefficient are presented in Table 4 in accordance with the suggested load duration.

Table 4. Value of k_{mod} for load duration according to EN 16612 standard [48]

Action	Load duration	Value of k_{mod}
Wind gust	5 s (or less)	1.0
Wind storm load	10 min	0.74
Maintenance loads	30 min	0.69
Snow load – external canopies and roofs of unheated buildings	3 weeks	0.45
Snow load – roofs of heated buildings	5 days	0.49
Dead loads, self-weight, altitude load on insulating glass units	Permanent (50 years)	0.29

By virtue of the k_{mod} coefficient values, glass assumes various design values of bending strength $f_{g,d}$ depending on the type of load. In Table 5, these values are presented for several types of glass: annealed float, thermally strengthened glass, and thermally toughened safety glass, as well as for selected loads. The lowest design value of bending strength occurs for permanent loads and annealed glass. In this case, the value only amounts to 18% of the characteristic value of the bending strength for this type of glass. The value equals 41% for thermally strengthened glass, while for thermally toughened safety glass, the value is 70%. However, it should be noted that the glass element is generally affected by the combination of loads. The standard recommends that in the case of combinations of loads, the k_{mod} coefficient at the highest possible value should be taken into account, i.e., for the shortest duration load. However, all relevant load combinations must be considered. The k_{mod} coefficient can also be determined as a weighted average [48].

Table 5. Design value of bending strength $f_{g,d}$ according to EN 16612 standard [48]

Condition of load	Load duration	Value of k_{mod}	Design value of bending strength fg, d
For annealed glass – float glass, $f_{g,k}$ = 45 [MPa] (formula 4.3)			
Permanent	15 years	0.32	$f_{g,d} = \frac{1 \cdot 0.32 \cdot 1 \cdot 45}{1.8} = 8.00$ [MPa]
Snow – roofs of heated building	5 days	0.49	$f_{g,d} = \frac{1 \cdot 0.49 \cdot 1 \cdot 45}{1.8} = 12.25$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = \frac{1 \cdot 1 \cdot 1 \cdot 45}{1.8} = 25.00$ [MPa]
For prestressed glass – heat strengthened glass, $f_{g,k}$ = 70 [MPa] (formula 4.4)			
Permanent	15 years	0.32	$f_{g,d} = \frac{0.32 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (70 - 45)}{1.2} = 28.83$ [MPa]
Snow – roofs of heated building	5 days	0.49	$f_{g,d} = \frac{0.49 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (70 - 45)}{1.2} = 33.08$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = \frac{1 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (70 - 45)}{1.2} = 45.83$ [MPa]
For prestressed glass – tempered glass, $f_{g,k}$ = 120 [MPa] (formula 4.4)			
Permanent	15 years	0.32	$f_{g,d} = \frac{0.32 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (120 - 45)}{1.2} = 70.50$ [MPa]
Snow – roofs of heated building	5 days	0.49	$f_{g,d} = \frac{0.49 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (120 - 45)}{1.2} = 74.75$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = \frac{1 \cdot 1 \cdot 45}{1.8} + \frac{1 \cdot (120 - 45)}{1.2} = 87.50$ [MPa]

4.2. Assumptions according to the draft standards prCEN/TS 19100

A design concept of structural glass contained in the draft standards prCEN/TS 19100 [44–46] significantly changes the approach to the safety of glass structures by extending the application of limit states. However, the basic verification of unfractured glass components still includes the ultimate limit state (ULS) and serviceability limit states (SLS).

4.2.1. Ultimate limit state (ULS)

In terms of the application of the ultimate limit state (ULS), it is specified that the design value of the effect of actions E_d shall not exceed the design value for resistance R_d for that combination:

$$E_d \leq R_d \tag{4.6}$$

The determination of the effect value of action E_d can occur through two cases. Firstly, E_d is considered as the design principal stress $\sigma_{\text{prin},Ed}$ on the surface of the glass in the main direction. Secondly E_d refers to the design sectional forces $N_{E,d}$, $V_{E,d}$, $M_{E,d}$ in the relevant direction. In this case the design strength R_d is calculated as the design bending strength of glass $f_{g,d}$ according to the following formula:

$$f_{g,d} = k_e \cdot k_{\mathrm{sp}} \cdot \lambda_A \cdot \lambda_l \cdot k_{\mathrm{mod}} \cdot \frac{f_{g,k}}{\gamma_M} + k_p \cdot k_{e,p} \cdot \frac{f_{b,k} - f_{g,k}}{\gamma_p} \tag{4.7}$$

where:
$f_{g,k}$ – characteristic value of bending strength for annealed glass,
$f_{b,k}$ – characteristic value of glass strength after a strengthening treatment,
γ_M – material partial factor, depends on the class of consequences, for the CC2$\gamma_M = 1.8$,
γ_p – partial factor for prestress on the surface, depends on the class of consequences, for the CC2$\gamma_p = 1.2$,
k_e – edge or hole finishing factor, for float glass with polished edges $k_e = 1.0$,
k_{sp} – surface treatment factor, for typical float glass $k_{\mathrm{sp}} = 1.0$,
k_{mod} – modification coefficient depending on load duration, accord to Table 4,
λ_A – size-effect factor area, for area 18 m^2 $\lambda_A = 1.0$,
λ_l – size-effect factor length (edge, hole), for length ≤ 6.0 m $\lambda_l = 1.0$,
k_p – coefficient accounting for the reduction of the process-induced prestressed, for float glass and polished edges $k_p = 1.0$,
$k_{e,p}$ – edge or hole prestressing factor,
for heat strengthened and thermally toughened (out of plane loading) $k_{e,p} = 1.0$,
for heat strengthened and thermally toughened (in-plane loading) $k_{e,p} = 0.8$.

The values of the design bending strength $f_{g,d}$ determined following the draft standard prCEN/TS 19100-1 [44] are influenced, among other things, by the k_{mod} coefficient values, similar to the 16612 standard [48]. Notably, the values of this coefficient are the same in both standards and depend on the type of load duration. The values of the design bending strength $f_{g,d}$ for different types of load duration are summarised in Table 6.

According to the draft standard prCEN/TS 19100-1 [44], design effects of actions E_d shall be determined according to EN 1990 [47] and EN 1991 [49] with all parts. In addition, the thermal load shall be considered in those cases where temperature differences can generate stress in the glass elements. Thermal stresses in the glass should be analysed to avoid thermal cracks by using thermal gradients – radial or stripe-pattern [50]. If the glass element is exposed to solar radiation, it heats up (usually the central part of the glass) due to absorption. The expanding heat then causes tensile stresses on the colder edges of the glass, which can cause local cracks, leading to the glass itself breaking (Fig. 4).

The stress caused by an uneven of thermal strains from the temperature differences can be obtained as follows:

$$\sigma_t = E \cdot \alpha_t \cdot \Delta T \tag{4.8}$$

where:
E – Young's modulus,
α_t – thermal expansion coefficient,
ΔT – the maximum temperature difference in the glass.

Table 6. Design value of the bending strength $f_{g,d}$ according to prCEN/TS 19100-1 [44]

Condition of load	Load duration	Value of k_{mod}	Design value of bending strength $f_{g,d}$
For annealed glass – float glass, $f_{g,k}$ = 45 [MPa] (formula 4.7)			
Permanent	15 years	0.32	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.32 \cdot \frac{45}{1.8} = 8.0$ [MPa]
Snow – roof of heat load building	5 days	0.49	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.49 \cdot \frac{45}{1.8} = 12.25$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot \frac{45}{1.8} = 25.0$ [MPa]
For prestressed glass – heat strengthened glass, $f_{g,k}$ = 70 [MPa] (formula 4.7)			
Permanent	15 years	0.32	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.32 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{70-45}{1.2} = 28.83$ [MPa]
Snow – roof of heat load building	5 days	0.49	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.49 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{70-45}{1.2} = 33.08$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{70-45}{1.2} = 45.83$ [MPa]
For prestressed glass – tempered glass, $f_{g,k}$ = 120 [MPa] (formula 4.7)			
Permanent	15 years	0.32	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.32 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{120-45}{1.2} = 70.50$ [MPa]
Snow – roof of heat load building	5 days	0.49	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 0.49 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{120-45}{1.2} = 74.75$ [MPa]
Wind gust load	3 s	1.0	$f_{g,d} = 1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot \frac{45}{1.8} + 1.0 \cdot \frac{120-45}{1.2} = 87.50$ [MPa]

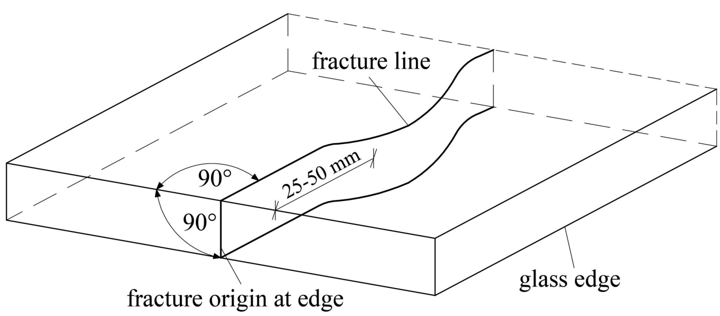


Fig. 4. Thermal fracture in glass pane

The reason for the stress concentration may be thermal stresses, but they can also occur in the supports or at the point of fixing the glass panes. The holes in the glass are particularly highlighted here. According to CEN/TS 19100-2 [45], the calculation of the stresses shall accurately take into account the possible local stress concentrations.

Theoretically, the stress concentration is characterised by the K_t coefficient (formula 4.9), which is defined as the ratio between the peak stress σ_{peak} at the root of the notch and the nominal stress σ_{nominal} [51]:

$$K_t = \frac{\sigma_{\text{peak}}}{\sigma_{\text{nominal}}} \tag{4.9}$$

The stress distribution near a circular hole under axial loading is presented in Fig. 5. In this case, the K_t factor can be obtained with different methods by calculations – analytical methods or finite-elements methods [52] or by measurements as photo-elastic measurements [53].

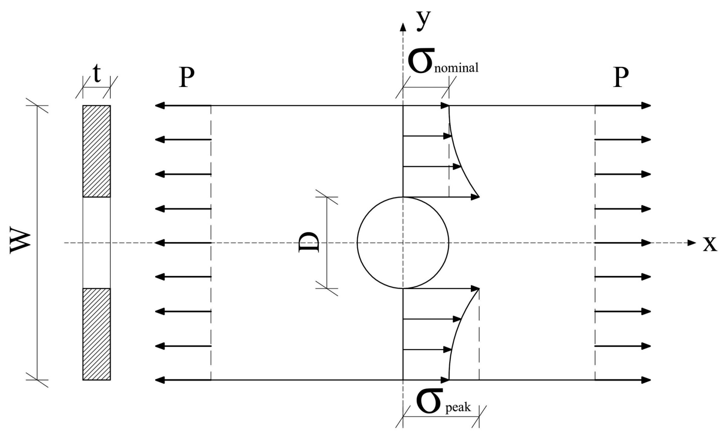


Fig. 5. Stress distribution near a circular hole under axial loading

4.2.2. Servisibility limit state (SLS)

In the serviceability limit state (SLS) was determined deformation classes for different levels of criticality:

- 1-SLS as deflections or displacements of pure aesthetical relevance,
- 2-SLS as deflections or displacements affecting integrity, functionality or durability of the glass component in the unfractured state,
- 3-SLS as deflection or displacements or effect thereof affecting safety.

The first class 1-SLS is not considered under this standard. For the second class 2-SLS, a typical deflection limit for glass components was defined, which are presented in Table 7.

In the case of the third class 3-SLS, it was recommended the glass chord shortening due to its deflection and to the tolerances. The recommended values of nominal mechanical edge cover for glass components are presented in Table 8.

Table 7. Deflection limits for glass components for deformations class 2-SLS according to prCEN/TS 19100-2 [45]

	Support condition	Deflection limit of the support of the edge		Deflection limit at a free edge		Deflection limit at centre	
		Monolith or laminated glass	IGU	Monolith or laminated glass	IGU	Monolith or laminated glass	IGU
Glass components without floors, stair treads, balustrades	Continuously supported along all edges	According to EN 13830: 2015 + A1:2020 [54]				$L/50_a$	
	Continuously supported along 2 or 3 edges	According to EN 13830: 2015 + A1:2020 [54]		$L/100_c$	$L/150_c$		
	Locally clamped along 2 or 3 edges	$L/150_b$		$L/100_c$		$L/50_a$	
	Point-fixed			$L/100_{c,d}$	$L/150_c$	$L/50_{a,d}$	

$_a$ – the length of the short edge, $_b$ – the distance between two point-fixings, $_c$ – the length of unsupported edge, $_d$ – Either the deflection limit of $L/100$ at the edge or $L/50$ in the centre should be applied, not together

Table 8. Recommended minimum nominal mechanical edge cover s for components of deformation class 3-SLS according to prCEN/TS 19100-2 [45]

Further specification	Minimum nominal mechanical edge cover or edge support depth s [mm]	
	Monolith or laminated glass	IGU
Vertical	12	12
Non-vertical	12	12

5. Effective thickness in the calculation of laminated glass

In glass structures, laminated glass is used due to the requirement to ensure safety. As a result of the use of polymer films or ionomer as the interlayer to hold the glass shards in the event of breakage, it is possible to obtain a minimum, but still substantial, load-bearing capacity of the laminated glass [10]. Therefore, it is essential to determine the degree of bonding of the individual layers, which is directly related to the transfer of shear forces. Three possible variants operate of laminated glass under bending can be distinguished.

In the first variant (Fig. 6a), it is assumed that the glass layers cooperate in the same way as in monolithic glass – that is, they transfer full shear. The third variant (Fig. 6c) comprises the case in which these forces are not transferred, which means that individual glass panes of the multi-layered panel operate separately. However, in reality, there are intermediate situations, e.g., partial shear transfer (Fig. 6b) [55]. The operation of laminated glass is determined by the shear transfer coefficient, defined in various ways in standards and source literature. The coefficient value provides the basis for determining the effective thickness of laminated glass.

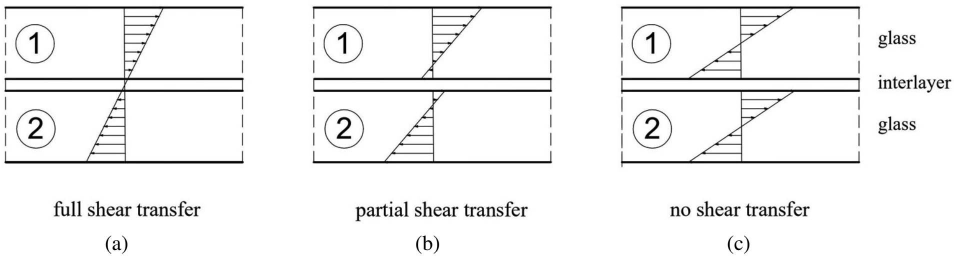


Fig. 6. Possibility of shear transfer and associated stress distribution under bending [55]

In the most recent European standard, EN 16612 [48], a simplified method for determining the effective thickness, called "equivalent thickness", is provided, which takes into account different calculation methods for the thickness of laminated glass in the event of deflection and stresses. In the case of deflection calculations, the following correlation is indicated:

$$t_{\mathrm{ef},w} = \sqrt[3]{\sum_{i=1}^{n} h_i^3 + 12 \cdot \omega \cdot \sum_{i=1}^{n} \left(h_i \cdot d_i^3\right)} \tag{5.1}$$

however, the following formula is applied in order to calculate stresses:

$$t_{\mathrm{ef},\sigma,i} = \sqrt{\frac{\left(h_{\mathrm{ef},w}\right)^3}{h_i + 2 \cdot \omega \cdot d_i}} \tag{5.2}$$

where:
h_i – thickness of the glass panes,
d_i – distance according to Fig. 7,
ω – coefficient for the shear transfer of an interlayer in laminated glass.

In formulas (5.1) and (5.2), the coefficient ω, which assumes a value from 0 to 1, is crucial. Its value $\omega = 0$ represents no bonding of laminated glass, whereas for the value of $\omega = 1$ complete bonding. For intermediate situations varying between 0 and 1, this coefficient ω was determined in a tabular manner and depends on the load types, load duration and, indirectly, on the interlayer properties (depending on the value of the G modulus). In order to determine the properties of the interlayers, so-called interlayer families, marked as 0, 1, and 2, were introduced [48, 56]. Family 0 comprises, for instance, a film with acoustic properties. Family 1 consists of the typical PVB film, while family 2 includes films used in structural solutions, such as SentryGlas® [24]. For each of the interlayer families, the coefficient ω was determined depending on the type of load and its duration (Table 9), as it was in the case when determining the k_{mod} coefficient [48, 56, 57].

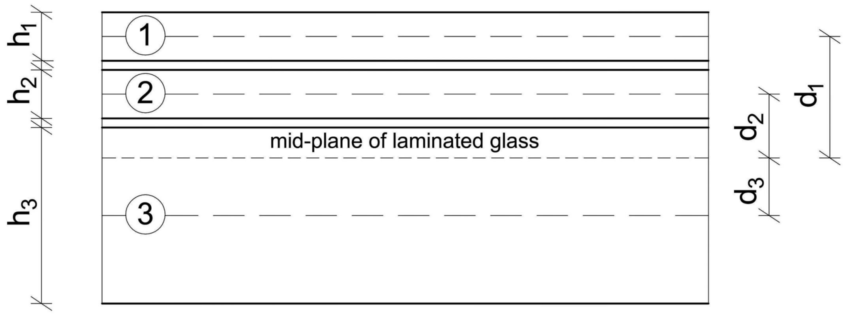


Fig. 7. Laminated glass composed of multi-layered glass panes

Table 9. Value of coefficient ω for different family interlayers and loads according to EN 16612 [48]

Action	Family 0	Family 1	Family 2
Wind gust	0	0.3	0.7
Wind storm load	0	0.1	0.5
Maintenance loads	0	0	0.1
Snow load – external canopies and roofs of unheated buildings	0	0.1	0.3
Snow load – roofs of heated buildings	0	0	0.1
Dead loads, self-weight, altitude load on insulating glass units	0	0	0

In accordance with the method specified in the EN 16612 standard [48], when calculating the effective thickness for laminated glass (Table 10), it can be noticed that for laminated glass made up of two glass panes of 5 mm thickness, bound with a film of 0.76 mm thickness (with 10.76 mm as the total thickness of the laminated glass), the lowest values of the effective thickness are obtained for permanent loads and equal 59% of its total thickness for deflection, and 66% for stress.

However, the simplified method for determining the effective thickness in laminated glass in the EN 16612 standard [48] raises some reservations [10,58]. Its primary disadvantage lies in the lack of a comprehensive approach, including no reference to the interlayer thickness or boundary conditions. On the other hand, the advantage of the method lies in the possibility of determining the laminated glass thickness for a multi-layered panel.

On the other hand, the Wölfel-Bennison approach [25] is more accurate in determining the effective thickness. It is based on the study on composite beams conducted by Wölfel [59] and was further developed for laminated glass by Bennison [60, 61]. This approach was formulated for a two-layered simply supported laminated beam under a uniformly distributed load. The key element of this method relies on the determination of the shear transfer coefficient Γ, which assumes values ranging from 0 to 1. Under certain conditions, the approach can be applied for laminated plates composed of two layers [62, 63].

Table 10. Equivalent thickness value of laminated glass according to EN 16612 [48] and EN 16613 standard [56]

Type of load	Load duration	Value of ω for family 2	Equivalent thickness for laminated glass glass 5 [mm] + PVB 0.76 [mm] + glass 5 [mm]
Permanent	15 years	0	$t_{\text{ef},w} = \sqrt[3]{2\cdot 5^3 + 12\cdot 0\cdot 2\cdot 5\cdot 2.88^2} = 6.30$ [mm]
			$t_{\text{ef},\sigma,i} = \sqrt{\dfrac{6.30^3}{5+2\cdot 0\cdot 2.88}} = 7.07$ [mm]
Snow – roofs of heated buildings	5 days	0.1	$t_{\text{ef},w} = \sqrt[3]{2\cdot 5^3 + 12\cdot 0,1\cdot 2\cdot 5\cdot 2.88^2} = 7.04$ [mm]
			$t_{\text{ef},\sigma,i} = \sqrt{\dfrac{7.04^3}{5+2\cdot 0.1\cdot 2.88}} = 7.91$ [mm]
Wind gust load	3 s	0.7	$t_{\text{ef},w} = \sqrt[3]{2\cdot 5^3 + 12\cdot 0.7\cdot 2\cdot 5\cdot 2.88^2} = 9.82$ [mm]
			$t_{\text{ef},\sigma,i} = \sqrt{\dfrac{9.82^3}{5+2\cdot 0.7\cdot 2.88}} = 10.24$ [mm]

This method was specified in the draft standard prEN 13474 [64] and was also implemented in the Italian standardisation document CNR-DT-210 [65].

Furthermore, the Wölfel-Bennison method was derived for one case only, i.e. for a simply supported two-layered beam or plates under a uniformly distributed load. An alternative approach for determining the effective thickness in laminated glass has recently been proposed, which is the Enhanced Effective Thickness (EET) method, by Galuppi and Carfagni [62, 66, 67]. This approach was also recommended together with the Wölfel-Bennison method in an Italian standardisation document [65, 68]. Currently, this method of determining the effective thickness in laminated glass has been included in the draft standard prCEN/TS 19100-2 [45] as the planned Eurocode 10.

In the Enhanced Effective Thickness (EET) method, the main parameter to determine the degree of layer bonding in laminated glass is the shear transfer coefficient marked as η and determined in the case of the two-layered laminated beams from the formula [45]:

$$\eta_{p,2} = \cfrac{1}{\displaystyle\int^{1+h} E \cdot \cfrac{D_{|\,|}\cdot h_1\cdot h_2}{\displaystyle\int^{G} (1-\upsilon^2)\cdot D_{\text{full}}(h_1+h_2)^{\Psi_p}}} \tag{5.3}$$

where:

D_{abs} – flexural stiffness at the layered limit, which is defined as: $D_{|\,|} = \sum\limits_{i=1}^{n} D_i = \dfrac{E\sum\limits_{i=1}^{n} h_i^3}{12\left(1-\nu^2\right)}$,

D_{full} – flexural stiffness at the monolith limit, which is defined as: $D_{\text{full}} = D_{|\,|} + \dfrac{E \sum_{i=1}^{n} \left(h_i \cdot d_i^2\right)}{\left(1 - \nu^2\right)}$,
h_1, h_2, h_i – glass thickness,
d_i – is distance accord to Fig. 7,
h_{int} – interlayer thickness,
E – Young's modulus of the glass,
G_{int} – shear modulus of the interlayer,
ν – Poisson coefficient,
ψ_p – boundary coefficient for plates.

The shear transfer coefficient η in formula (5.3) depends on the glass and the polymer interlayer properties, geometric conditions, but also the boundary conditions and the type of load expressed with the Ψ coefficient [45, 67]. The values of the Ψ, as well as the scope of its application, have been discussed in greater detail for plates in [62] and beams in [66]. In the case of plates and beams, it depends on the loading and support conditions. For plates, the Ψ coefficient values have been tabulated for the loading and support conditions shown in Fig. 8.

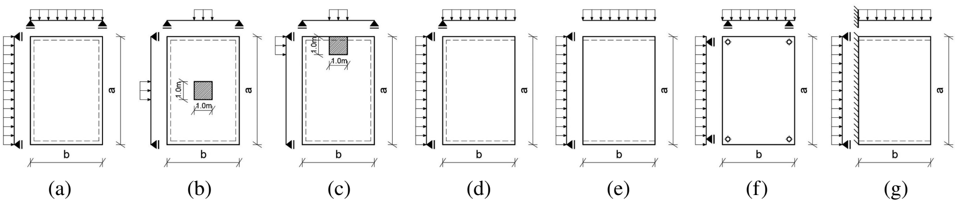


Fig. 8. Different loading and support conditions of laminated glass plates for determination of the Ψ coefficient according to prCEN/TS 19100-2 standard [45]

In the Enhanced Effective Thickness (EET) method, the effective thickness of the laminated glass for the two-layered plates is, therefore, determined when calculating deflection, according to the formula [45]:

$$h_{\text{ef},w} = \sqrt[3]{\dfrac{1}{\dfrac{\eta}{\sum_{i=1}^{n} h_i^3 + 12 \sum_{i=1}^{n}\left(h_i \cdot d_i^2\right)} + \dfrac{1-\eta}{\sum_{i=1}^{n} h_i^3}}} \tag{5.4}$$

whereas for the calculations of stress, according to the correlation [45]:

$$h_{\text{ef},\sigma,i} = \sqrt{\dfrac{1}{\dfrac{2 \cdot \eta \cdot |d_i|}{\sum_{i=1}^{n} h_i^3 + 12 \sum_{i=1}^{n}\left(h_i \cdot d_i^2\right)} + \dfrac{h_i}{h_{\text{ef},w}^3}}} \tag{5.5}$$

When calculating the effective thickness for a laminated glass plate in accordance with prCEN/TS 19100-2 [45], its geometry, loading and support conditions are taken into account. For a panel with dimensions of 1.5×2.0 m and supported on four edges (Fig. 6a), the Ψ coefficient is 6.969×10^{-6} mm^2 [45]. This glass is composed of two 5 mm thick glass layers glued with 0.76 mm PVB film. For such assumptions and for the wind load gust load (3 s), the shear transfer coefficient $\eta_{p,2} = 0.8042$ ($G_{\text{inst}} = 0.8$ MPa for time duration 3 s and temperature 50°C). The effective thickness for deflection is then $h_{\text{ef},w} = 9.31$ mm, while for stresses, it takes the value $h_{\text{ef},\sigma} = 10.04$ mm.

The Enhanced Effective Thickness (EET) method is now being developed not only for two-layered plates or beams [45], but also for other specifications such as multi-layered laminated glass [58], curved laminated glass [69], and cantilevered laminated glass balustrades [70].

Table 11 shows a collation of the main assumptions when determining the effective thickness in laminated glass, using the following methods: EN 16612 standard [48], prCEN/TS 19100-2 standard [45].

Table 11. Collation of the main assumptions of the method for calculating the effective thickness

<table>
<tr><td colspan="2">Method of calculation of the effective thickness</td><td>EN 16612</td><td>prCEN/TS 19100-2
Enhanced Efficient Thickness (EET)</td></tr>
<tr><td rowspan="3">Degree of shear transfer</td><td>Full shear transfer</td><td>$\omega = 1$</td><td>$\eta = 1$</td></tr>
<tr><td>Partial shear transfer</td><td>ω between 0 and 1</td><td>η between 0 and 1</td></tr>
<tr><td>No shear transfer</td><td>$\omega = 0$</td><td>$\eta = 0$</td></tr>
<tr><td colspan="2">Concept of the shear transfer coefficient</td><td>for multi-layered laminated glass
ω – values are tabulated</td><td>for two-layered glass plates
$\eta_{p,2} = \dfrac{1}{1+h \displaystyle\int E \cdot \dfrac{D_{\vert\vert} \cdot h_1 \cdot h_2}{G \displaystyle\int \left(1 - \upsilon^2\right) \cdot D_{\text{full}} \left(h_1 + h_2\right)^{\Psi_p}}}$</td></tr>
<tr><td colspan="2">Main difference in determining the value of the shear transfer coefficient</td><td>– interlayer stiffness family,
– type of loading, in particular, its characteristic duration and the environmental temperature</td><td>– coefficient Ψ depends on the loading and boundary conditions (for plates and beams)</td></tr>
</table>

6. Conclusions

Glass structures present a significant engineering challenge. Glass, as a brittle material, and works differently than typical structural materials that may work in the elastic or plastic stage. Therefore, it is essential to understand its strength properties and the nature of the static works of glass structural elements.

According to the European normative documents currently in force, great attention is paid to ensuring the safety of structures. If glass structures are to be implemented, it is crucial to use laminated glass technology as it maintains a residual load capacity in post-fracture conditions. Hence, it is assumed that the additional limit states will be introduced in the planned Eurocode 10 devoted to the design of glass structures. In addition to the ultimate limit state (ULS), and serviceability limit state (SLS), the fracture limit state (FLS), and the post-fracture limit state (PFLS) will be introduced.

Due to the operation of laminated glass within the structural element, the interlayer and its strength properties have a significant influence. The new generation polymer and ionomer interlayers are characterised by better strength properties [71]. However, it should be emphasised at this point that the properties of such materials depend on the load duration and ambient temperature. Thus, further research is required due to the operation time of glass structures.

The European standards currently in force indicate methods for calculating laminated glass working as coupled or uncoupled or in an intermediate situation of glass sheets; therefore, the so-called effective thickness is calculated. However, it should be emphasised that the method for calculating effective thickness that is presented in the standards are most useful in the design of glass plates. In the case of other elements, the situation is more complicated. One of the reasons is the direction of load, i.e., out-of-plane or in-plane. On the other hand, the direction of the glass layers is also important, which can be horizontal or vertical. Also, in this respect, further research is required.

References

[1] C.J. De Lima, F. Veer, O. Çopuroglu, R. Nijsee, "Advancements and Challenges in Glass Concepts, Manufacturing and Applications", presented at 13th International Congress on Advances in Civil Engineering, 12-14 Sep. 2018, Izmir, 2018.

[2] Ch. Schittisch, "Glass Pavilion at Broadfield House in Kingswinford Architecture", in *Auf Den Zweiten Blick / Architecture and the Test of Time*, K. Arima, et. al. Munich: Detail, 2012.

[3] M. Marchewka, "Advances in the Use of Structural Glass", in *Challenging Glass 2: Conference on Architectural and Structural Applications on Glass*, J. Bos, Ch. Louter, R. Veer, Eds. Delf, 2010.

[4] J. O'Callaghan, "Adventures with Structural Glass", *Glass Performance Days*, South Africa, 2012.

[5] Ch. Bedon, M. Santarsiero, "Transparency in Structural Glass Transparency Via Mechanical Adhesive and Laminated Connections – Existing Research and Developments", *Advanced Engineering Materials*, 2018, vol. 20, no. 5, pp. 1–18, DOI: 10.1002/adem.201700815.

[6] M. Teich. Ch. Bauchinger, "Aktuelle Entwicklungen und Konstruktionstechniken für Glasfassaden", *Bautechnik*, 2020, vol. 97, pp. 338–343, DOI: 10.1002/bate.202000014.

[7] A. Jóźwik, "O możliwościach zastosowania szkła w elementach konstrukcyjnych", *Inżynieria i Budownictwo*, 2017, vol. 9, pp. 459–462.

[8] TU0905 – Structural Glass – Novel design methods and next generation products. [Online]. Available: https://www.cost.eu/actions/TU0905/. [Accessed: 10.07.2021].

[9] M. Feldman, R. Kasper, et al., *Guidance for European Structural Design of Glass Components*. 2014.

[10] M. Kozłowski, *Balustrady szklane. Analizy doświadczalne obliczeniowe, podstawy projektowania*. Gliwice: Wydawnictwo Politechniki Śląskiej, 2019.

[11] H. Zobel, "Normalizacja w procesie projektowania w budownictwie". [Online]. Available: https://www.piib.org.pl/ aktualnosci/informacje-biezace/4472-normalizacja-w-procesie-projektowania-w-budownictwie. [Accessed: 10.07.2021].

[12] M. Haldimann, A. Luible , M. Overen, *Structural use of glass.* Zürich: IABSE, 2008.

[13] N.I. Min'ko, V.M. Nartsev, "Factors Affecting the Strength of the Glass", *Middle-East Journal of Scientific Research*, 2013, vol. 18, no. 11, pp. 1616–1624.

[14] A.A. Griffith, "The phenomena of rupture and flow in solids", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 1921, vol. 221, no. 582–593, DOI: 10.1098/rsta.1921.0006.

[15] EN 572-1:2012+A1:2016 *Glass in building – Basic soda lime silicate glass products – Part 1: Definitions and general physical and mechanical properties*.

[16] EN 1863-1:2011 *Glass in building – Heat strengthened soda lime silicate glass – Part 1: Definition and description*.

[17] EN 12150-1:2015+A1:2019 *Glass in building – Thermally toughened soda lime silicate safety glass – Part 1: Definition and description*.

[18] EN 12337-1:2000 *Glass in building – Chemically strengthened soda lime silicate glass – Part 1: Definition and description*.

[19] M. Martin, X. Centelles, A. Solé, C. Barreneche, A.I. Fernández, L.F. Cabeza, "Polymeric interlayer materials for laminated glass: A review", *Construction and Building Materials*, 2020, vol. 230, DOI: 10.1016/j.conbuildmat.2019.116897.

[20] J. Schneider, "Performance Comparision of Structural Interlayers", in *Challenging Glass 6: Conference on Architectural and Structural Applications on Glass*, Ch. Louter, et al., Eds., 2018, vol. 6, DOI: 10.7480/cgc.6.2202.

[21] Trosifol®Architectural Glazing for architects, designers, engineers and consultants. [Online]. Available: https://www.trosifol.com/fileadmin/user_upload/TROSIFOL/support/downloads/product_brochures/pdf_documents/architecture/Trosifol_SentryGlas_Architectural-Glazing.pdf. [Accessed: 10.07.2021].

[22] SentryGlas® Ionoplast Interlayer. [Online]. Available: https://www.trosifol.com/fileadmin/user_upload/technical_information/downloads/sentryglas/150129_Kuraray_TM_Datenblatt_SG.pdf. [Accessed: 10.07.2021].

[23] W.M. Stevels, P.D. Haene, P. Zhang, S. Haldeman, "A Comparison of Different Methodologies for PVB Interlayer Modulus Characterization", in *Challenging Glass 5: Conference on Architectural and Structural Applications on Glass*, vol. 5, J. Belis, F. Bos, Ch. Louter, Eds. Ghent, 2016, DOI: 10.7480/cgc.5.2266.

[24] W.M. Stevels, "PVB Interlayer Modulus Properties in Contemporary European Standards", *Glass Performance Days*. Tampere, 2019, pp. 56–60.

[25] M. Gwóźdź, *Konstrukcje szklane i aluminiowo-szklane*. Kraków: Wydawnictwo Politechniki Krakowskiej, 2020.

[26] J. Belis, J. Depauw, D. Callewaert, D. Delincé, R. Van Impe, "Failure mechanisms and residual capacity of annealed glass/SGP laminated beams at room temperature", *Engineering Failure Analysis*, 2009, vol. 16, no. 6, pp. 1866–1875, DOI: 10.1016/j.engfailanal.2008.09.023.

[27] A. Kott, "Zum Trag- und Resttragverhalten von Verbundsicherheitsglas", Doctoral Thesis ETH Zürich, 2006, Prof. T. Vogel, Prof. Dr. K. Begmeister, DOI: 10.3929/ethz-a-005170632.

[28] G. Siebert, "Aktueller Stand der Glasnormung", *Stahlabu*, 2015, vol. 84, no. S1, pp. 21–29, DOI: 10.1002/stab.201590079.

[29] T. Wüest, A. Luible, "Glass Design in Switzerland", in *Challenging Glass 7*, vol. 7, J. Belis, F. Bos, Ch. Louter, Eds. Ghent, 2020, DOI: 10.7480/cgc.7.4610.

[30] TRLV Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen (Technical rules for the use of glazing with linear supports), DIBt, August 2006.

[31] TRPV Technische Regeln für die Bemessung und Ausführung punktförmig gelagerter Verglasungen (Technical rules for the use of glazing with supports at individual points), DIBt, August 2006.

[32] TRAV Technische Regeln für die Verwendung von absturzsichernden Verglasungen (Technical rules for the use of safety-barier glazing), DIBt, January 2003.

[33] A. Haese, G. Siebert, "DIN 18008 – Experience after one year of applying the new German glass design standard", in *Challenging Glass 5: Conference on Architectural and Structural Applications on Glass*, J. Belis, F. Bos, Ch. Louter, Eds. Ghent, 2016, DOI: 10.7480/cgc.5.2288.

[34] DIN 18008-1:2010-12 (currently DIN 18008-1:2020-05) *Glass in building – Design and construction rules – Part 1: Terms and general bases*.

[35] DIN 18008-2:2010-12 (currently DIN 18008-1:2020-05) *Glass in building – Design and construction rules – Part 2: Linearly supported glazing*.

[36] DIN 18008-3:2013-07 *Glass in building – Design and construction rules – Part 3: Point fixed glazing*.

[37] DIN 18008-4:2013-07 *Glass in building – Design and construction rules – Part 4: Additional requirement for safety-barrier glazing*.

[38] DIN 18008-5:2013-07 *Glass in building – Design and construction rules – Part 5: Additional requirement for walk-on glazing*.

[39] DIN 18008-6:2018-02 *Glass in building – Design and construction rules – Part 6: Additional requirement for walk-on glazing in case of maintenance procedures and for fall-through glazing*.

[40] G. Siebert, "Comparison of IGU-design according to German and European Standards", *Engineered Transparency 2018: Glass in Architectural Engineering*, 2018, vol. 2, no. 5-6, pp. 81–92, DOI: 10.1002/cepa.912.

[41] G. Siebert, M. Botz, M.A. Kraus, "Comparison of LSG-design according to German and European Standards", in: *Engineered Transparency 2018. Glass in Architecture and Structural Engineering*, J. Schneider, B. Weller, Eds. Berlin: Ernst und Sohn, 2018, vol. 2, no. 5-6, pp. 93–102, DOI: 10.1002/cepa.913.

[42] A. Piekarczuk, "Projektowanie konstrukcji ze szkła budowlanego. Dokumenty normatywne", *Budownictwo i Prawo*, 2018, vol. 21, no. 2, pp. 10–13.

[43] M. Feldmann, P. Di Biase, "The CEN-ST "Structural Glass – Design and Construction" as pre-standard for the Eurocode", *Ce/papers*, 2018, vol. 3, no. 1, pp. 73–82, DOI: 10.1002/cepa.1001.

[44] CEN/TS 19100-1:2021 *Design of glass structures – Part 1: Basis of design and materials*.

[45] CEN/TS 19100-2:2021 *Design of glass structures – Part 2: Design of out-of-plane loaded glass components*.

[46] CEN/TS 19100-3:2021 *Design of glass structures – Part 3: Design of in-plane loaded glass components and their mechanics joints*.

[47] EN 1990:2002+A1:2005 *Eurocode – Basis of structural design*.

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

[49] EN 1991 *Eurocode 1: Actions on structures*.

[50] P. Foraboschi, "Analytical modeling to predict thermal shock failure and maximum temperature gradients of a glass panel", *Material & Design*, 2017, vol. 134, pp. 301–319, DOI: 10.1016/j.matdes.2017.08.021.

[51] J. Schijve, *Fatigue of Structures and Materials*. Dordrecht: Springer, 2009.

[52] N. Pourmoghaddam, J. Schneider, "Finite-element analysis of the residual stresses in tempered glass plates with holes or cut-outs", *Glass Structural Engineering*, 2018, no. 3, pp. 17–37, DOI: 10.1007/s40940-018-0055-z.

[53] G. Šaučiuvenas, T. Gečys, A. Mudrov, L. Ustinovichius, Cz. Miedzialowski, "The analysis of stress distribution in tempered structural glass with stress concentrators under tension and compression", *Archives of Civil and Mechanical Engineering*, 2020, vol.20, no. 3, pp. 66–77, DOI: 10.1007/s43452-020-00067-5.

[54] EN 13830:2015 +A1:2020 *Curtatin walling – Product standard*.

[55] J. Kuntsche, M. Schuster, J. Schneider, "Engineering design of laminated safety glass considering the shear coupling: a review", *Glass Structural Engineering*, 2019, vol. 4, pp. 209–228, DOI: 10.1007/s40940-019-00097-3.

[56] EN 16613:2019 *Glass in building – Laminate glass and laminated safety glass – Determination of interlayer viscoelastic properties*.

[57] M.A. Kraus, M. Botz, G. Siebert, "Structural Design of Laminated Glass Under Consideration of the Shear Coupling According to German, European an US Standards", Conference paper GlassCon Global, Chicago, 2018.

[58] L. Galuppi, G. Royer-Carfagni, "Enhanced Effective Thickness of multi-layered laminated glass", *Composites Part B: Engineering*, 2014, vol. 64, pp. 202–213, DOI: 10.1016/j.compositesb.2014.04.018.

[59] E. Wölfel, "Nachgiebiger Verbund Eine Näherungslösung und deren Anwendungsmöglichkeiten", *Stahlbau*, 1987, vol. 56, no. 6, pp. 173–180.

[60] S.J. Bennison, I. Stelzer, "Structural properties of laminated glass. Short course", *Glass Performance Days,* Tampere, 2009.

[61] I. Calderone, P.S. Davies, S.J. Bennison, H. Xiaokun, L. Gang, "Effective laminated thickness for the design of laminated glass", *Glass Performance Days*, Tampere, 2009, pp. 1–3.

[62] L. Galuppi, G. Royer-Carfagni, "The effective thickness of laminated glass plates", *Journal of Mechanics of Materials and Structures*, 2012, vol. 7, no. 4, pp. 375–400, DOI: 10.2140/jomms.2012.7.375.

[63] M. Gwóźdź, P. Woźniczka, "New static analysis methods for plates made of monolithic and laminated glass", *Archives of Civil Engineering*, 2020, vol. 66, no. 4, pp. 593–603, DOI: 10.24425/ace.2020.135239.

[64] EN 13474-1:1999 *Glass in building – Design of glass panes – Part1: General basis of glass*.

[65] CNR-DT 201:2013 *Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Costruzioni con Elementi Strutturali di Vetro (Guide for the Design, Construction and Control of Buildings with Structural Glass Elements)*.

[66] L. Galuppi, G. Royer-Carfagni, "Effective thickness of laminated glass beams: New expression via a variational approach", *Engineering Structures*, 2012, vol. 38, pp. 53–67, DOI: 10.1016/j.engstruct.2011.12.039.

[67] L. Galuppi, G. Royer-Carfagni, "Practical expressions for the design of laminated glass", *Composites: Part B,* 2013, vol. 45, no. 1, pp. 1677–1688, DOI: 10.1016/j.compositesb.2012.09.073.

[68] L. Galuppi, G. Royer-Carfagni, "The effective thickness of laminated glass: Inconsistency of the formulation in proposal of EN-standards", *Composites: Part B*, 2013, vol. 55, pp. 109–118, DOI: 10.1016/j.compositesb.2013.05.025.

[69] L. Galuppi, G. Royer-Carfagni, "Enhanced effective thickness (EET) of curved laminated glass", *Annals Solid Structural Mechanics,* 2015, vol. 7, pp. 71–92, DOI: 10.1007/s12356-015-0043-9.

[70] A. Nizich, L. Galuppi, "Enhanced Effective Thickness method for Cantilevered Laminated Glass Balustrades", *Glass Performance Days*, Tampere, 2019, pp. 398–401.

[71] J. Schneider, "Next generation ionoplast for improved lamination", *Glass Performance Days*, Tampere, 2019, pp. 61–63.

Wprowadzenie do projektowania szkła konstrukcyjnego według aktualnych norm europejskich

Słowa kluczowe: konstrukcje szklane, szkło konstrukcyjne, szkło laminowane, EN 16612, CEN/TS-19100, Eurokod 10

Streszczenie:

Szkło jest materiałem powszechnie stosowanym w budownictwie. Rozwój jego technologii oraz wzrost wiedzy dotyczącej właściwości mechanicznych i wytrzymałościowych sprzyja również możliwościom stosowania szkła jako materiału konstrukcyjnego. Konstrukcyjne zastosowanie szkła jest szczególnie istotne dla kształtowania rozwiązań architektonicznych, w których transparentność stanowi szczególną cechę estetyczną.

Wraz z rozwojem konstrukcji szklanych są opracowywane metody ich projektowania oraz wytyczne i normy w tym zakresie. W artykule scharakteryzowano podstawowe właściwości szkła jako materiału konstrukcyjnego. Ponadto omówiono główne założenia wytycznych niemieckich TRxV, serii niemieckich norm DIN 18008 oraz norm europejskich (mających również status polskich norm) PN-EN 16612 wraz z EN 16613. Artykułprzedstawia także koncepcję projektowania szkła konstrukcyjnego zawartą w projekcie normy CEN/TS 19100, która stanowi podstawę opracowania zharmonizowanej normy Europejskiej – Eurokodu 10 dotyczącego projektowania konstrukcji szklanych. Zgodnie z tą prenormą szklane elementy konstrukcyjne będą weryfikowane ze względu na ich bezpieczeństwo w oparciu o cztery stany graniczne w zależności od tzw. klasy konsekwencji pęknięć. Oprócz klasycznych stanów granicznych, tj. stanu granicznego nośności i stanu granicznego użytkowalności, zakłada się również wprowadzenie stanu granicznego pęknięcia i stanu granicznego po pęknięciu.

W artykule poruszono także kwestię pracy szkła laminowanego w elementach konstrukcyjnych. W zależności od stopnia zespolenia tafli szklanych i międzywarst polimerowych lub jonomerowych, można wyróżnić szkło laminowane całkowicie zespolone, lub niezespolone, a także pracujące w sytuacjach pośrednich. Biorąc pod uwagę charakter pracy szkła laminowanego, przy jego projektowaniu oblicza się tzw. grubość efektywną. W artykule omówiono metody wyznaczania grubości efektywnej zawarte w europejskich normach i wytycznych.

Received: 02.08.2021, Revised: 20.09.2021