RESEARCH PAPER

New Swiss technical specification SIA 2057 for glass structures and its post failure limit state concept

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Abstract Until recently, designing and constructing with glass in Switzerland was not performed on a uniformly regulated basis due to the lack of a national standard for glass. Therefore, foreign regulations and codes were typically applied. However, this practice repeatedly caused problems. In August 2021, the Technical Specification SIA 2057 Glass Structures has been published to close this codification gap and to create a uniform design basis for the Swiss glass industry. A wide range of glass applications is covered, taking into account the latest findings from practice and science, such as use of shear transfer in laminated glass. The SIA 2057 follows the well-proven SIA principles of regulating only where necessary. Thus, a flexible application of the code is made possible, and innovation is encouraged. In addition to simple design methods, engineers are free to pursue alternative and innovative paths in glass design. The present article provides an overview of the SIA 2057 with focus on laminated safety glass design and post fracture limit state verification.

Keywords Glass · Laminated glass · Post fracture limit state

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1 Introduction

In Switzerland, there was no glass design standard or technical specification available until 2021. In addition, the European standard on glass design is under development. As the European standard on glass design is still under development and could thus not yet be applied, a standard commission was established in Switzerland to draw up a technical specification for glass design. This allowed respecting the principles of the future European glass standard in order to facilitate later harmonization. As a result, the Swiss standard commission issued the Technical Specification SIA 2057 in 2021 (SIA 2021).

To understand the development and codification procedure in Switzerland and the inter-dependency between European Standards (EN) and Swiss Standards (SN, SIA), an outline of this topic is given below, see Fig. 1.

In Switzerland, the SNV (Swiss Standards Organization) organizes standardization work and represents Swiss interests in European and international standardization. Therefore, the SNV is a full (and founding) member of the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). The SNV is in direct relation to the state secretariat for economy (SECO) which supervises the notification of technical regulations.

Based on the Technical Barriers to Trade (TBT) Agreement, Switzerland is obliged to harmonize Swiss technical regulations with those of the EU. The SNV

Fig. 1 Organization diagram of the Swiss development process for standards. *Seco* State secretariat for economy Switzerland, *SNV* Swiss Standards Organization, *SIA* Swiss Society of Engineers and Architects, *EU* European Union, *CEN* European Committee for Standardization, *EN* European Standard *TS* Technical Specification, *TR* Technical Report
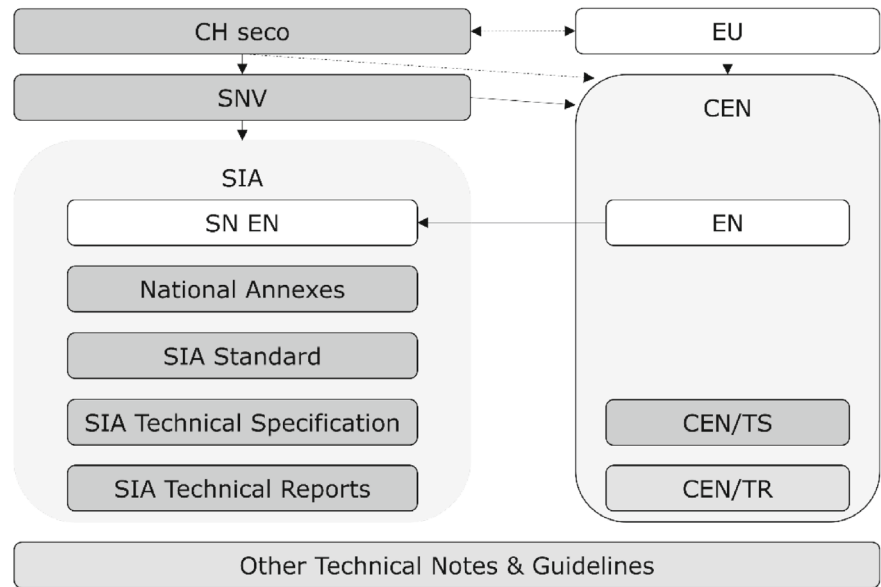
is the national standard body in Switzerland and coordinates the adaption and publication of European standards. The SNV also transposes all European standards as identical national standards and withdraws or adapts any conflicting national standards.

The SNV is supported by various institutions for the implementation of the standards in the relevant departments. With respect to construction industry, the Swiss Society of Engineers and Architects (SIA) is responsible owing to its role as Switzerland's principal professional association for the construction, technology, and environment sector. The SIA develops, updates and publishes numerous standards, regulations, technical specifications, recommendations and documentation for the Swiss construction industry.

Based on the TBT Agreement, harmonized EN Standards are valid in Switzerland. The SIA is responsible for preparing the corresponding national specifications and annexes for the EN standards for the construction sector and withdraw conflicting standards. Where a SN EN exists, the corresponding SIA Standard has the status of an adequate implementation of the European standard.

The development of new SIA standards is based on voluntary work by working groups or SIA committees from the relevant field. In contrast to EN Standards,

there are no "draft SIA standards" or "prSIA". If a completely new standard is developed, it becomes a "Technical Specification" first. Such a "Technical Specification" can be described as publications having a normative character. The specifications are developed by a committee of the SIA. By means of their practical application, the necessary experience should be gained, which can serve as a basis for the development of the resulting regular SIA standard. A Technical Specification is valid for five years. Before the end of these five years, a decision must be made as to whether a Technical Specification will be incorporated into a standard, a regulation or a set of guidelines, or whether it will be deleted without replacement.

In cases, where no SN EN or SIA standard exists, other relevant technical notes, guidelines or foreign standards are typically used as a reference in Switzerland.

How legally binding such technical notes or guidelines are depends on the status and recognition of the publisher. As an example, the SIGAB (Swiss Institute for Glass in Buildings) can be cited, which is a well-recognized organization for all building glazing topics. In case of dispute in court, SIGAB guidelines are likely to be consulted even if they thought they might not have normative status from SIA or SNV.

2 The technical specification SIA 2057

2.1 Genesis of SIA technical specification 2057

Before the release of SIA technical specification 2057, no national document regulated the use of glass in buildings. Only within the SIA 329:2018 Curtain Walls SIA (2018) and SIA 331:2012 Windows and door height windows SIA (2012), allowable bending stresses for glass were listed in an annex. However, both standards are not conform with the SIA 260 series standards which are based on the semi probabilistic design concept (comparable to the Eurocodes (SN EN 2002). In addition, there was a lack of rules how to apply those allowable stresses.

The SIGAB was the first institution that took care about the use of glass in buildings. Since 1980, the SIGAB published recommendations and guidelines concerning safety issues of glass (SIGAB 2017) (SIGAB 2007). The guidelines proposed simple design tables and methods to determine minimal glass thickness, which were based on best practice or foreign standards. Since 1998 the application of the German TRLV (technical regulations for linear supported glazing) (TRLV 2006) became widespread in Switzerland.

In 2010, the DIN 18008-1 (2010) and -2 DIN (2020) replaced the TRLV in Germany. The transition from TRLV to DIN 18008 changed the safety concept from deterministic (allowable stress) to the semi-probabilistic (design values). Thus, the safety concept of DIN 18008 and SIA 260 were based on the same principle in harmony with European Standard EN 1990 (Eurocode 0 or EC 0) (SN EN 2002). These changes again revealed the regulation gap for glass design in Switzerland and brought about the necessity to modernize and regulate glass design codification adopted to Swiss requirements.

As a consequence, the SIA, SIGAB and the Competence Centre Building Envelope and Civil Engineering (CC GH + IB) at the Lucerne University of Applied Sciences and Arts initiated the development of a national glass standard. The resulting SIA Committee 268, which consists of representatives of the glass industry, designers, façade manufacturers, façade engineers and research institutions started the task to develop a new glass design standard for Switzerland in 2014. The result was the "Technical Specification SIA 2057" which was released in August 2021. This technical specification is designed to use best practice, to

allow innovative solutions and it is compatible with the prCEN/TS 19100 (2020) (future EN 19100).

The following sections provide a general overview of the principles adopted and give a comprehensive summary of the content. In addition, specific design methods and regulations are explained in detail.

2.2 The SIA principles

For SIA standards, great importance is given to the ease of use. Therefore, most of the structural design standards consist only of one single document with all the information necessary. Furthermore, the standard is not intended to cover all possible application situations, but only the most relevant from a practical point of view. In cases which are not directly addressed by the standard, the engineer is responsible for implementing the safety standards to the best of his knowledge.

The use of SIA standards is not mandatory unless contractually agreed upon (which is usually the case). Although no standards are specified in laws and building regulations, they are considered state-of-the-art in the event of damage. In Switzerland, there are no "general construction technique permits" (aBG), "national technical approvals" (abZ) or checking bodies such as design review engineers as it is the case in Germany, as an example. In contrast, in Switzerland it is the responsibility of the engineer to design according to the state-of-the-art and to provide the respective safety concept, especially if no standard exists.

In this sense of engineering responsibility, the SIA 2057 is intended to enable solid, economical, safe and robust glass design based on theory, best practice and latest developments. Restrictions with respect to construction are reduced to a minimum to allow liberal and innovative design solutions. SIA 2057 provides the following verification alternatives for design engineers:

1. The intended design fully complies with SIA 2057 and the related codes (e.g. SIA 260 and 261);
2. Minor deviations from SIA 2057 that necessitate additional verification, such as a risk analysis;
3. Major deviations from SIA 2057 that result in additional theoretical and/or test-based verification and documentation obligations by the engineer.

2.3 General content overview of SIA 2057

The introductory Sections 0 to 2 treat the scope, terms/definitions, principles and normative references used throughout the document. Section 3 of SIA 2057 deals with involved materials and their properties. In addition, necessary general requirements and specification regarding interlayers (such as time- and temperature-dependent viscoelastic data), glass support, load local load transfer and imperfections for stability verification are listed.

Section 4 contains basic aspects essential for the structural design, analysis and dimensioning. This includes additional specifications regarding load combinations not regulated in SIA 260 (2013) [equivalent to EN 1990 (SN EN 1990)]. Also, glass-specific stipulations, e.g. the use of nominal thickness for glass dimensioning, are recorded. Furthermore, the consideration of shear transfer for dimensioning laminated safety glass (LSG) is regulated, refer to Sect. 0 in the present article. Comparable to prCEN/TS 19100-1:2020 (2020), a four limit states concept (Service limit state SLS, ultimate limit state ULS, fracture limit state FLS, post-fracture limit state PFLS) has been established, which is shown in detail in Sect. 0 below.

Section 5 deals with the components, such as vertical glazing, insulated glazing units or glass balustrades. For each component additional requirements for construction and the four limit states are set. A glazing can be subject to several component categories and thus needs to fulfill the combined requirements of these categories.

Section 6 deals with supports and connections. In addition to general points, requirements for local supports or adhesive connections are also mentioned. In case of structural glazing, all four support configuration types I to IV according to EN 13022 (EN 2014) are authorized.

Section 7 treats the test-based design. This chapter is divided in three subchapters to deal with different types of testing; i) project-specific material strengths, ii) test-based verification of design hypotheses and iii) load-bearing tests of glass components.

In the annexes, additional information about temperatures of components, load duration, residual capacity tests, insulated glazing unit (IGU) temperatures, climate loads and pendulum impact testing is given. Refer to Table 1 below for an overview of the section titles

Table 1 Content overview and structure of SIA 2057 and focus on Sects. 4 and 5

Section	Title
0	Scope of application
1	Terms and definitions
2	Principles of application
3	Materials
4	Structural analysis and dimensioning
	Structural analysis principles
	Four limit states: SLS, ULS, fracture limit state (FLS) and post
	fracture limit state (PFLS)
5	Building components (9 categories)
	Vertical and horizontal glazing
	IGU
	Barrier glazing / fall prevention
	Glazing accessible for maintenance, accessible glazing and
	accessibility for vehicles
	Structural glass members subjected to compression (columns) or bending (beams, stiffeners), stability topics
6	Supports, joints, connections
7	Execution, realization
8	Durability / endurance
9	Test-based dimensioning
Annex A	Load duration and temperature for LSG compound (normative)
Annex B	Post-breakage / residual load capacity (informal)
Annex C	Pendulum impact test (informal)
Annex D	Climate load (normative)
Annex E	Edge protection (informal)

and the content of the Sects. 4 and 5 treated in more detail in the present paper.

2.4 Design bending strength

The design bending strength $f_{g,d}$ is to be determined according to Eq. 1, whereby the compact form is based on nominal product strength according to Table 2 below. Comparable to prCEN/TS 19100 the Eq. 1 for design bending strength is generally defined for

Table 2 Characteristic tensile bending stress and related normative base

Glass type	Charact. tensile bending stress $f_{g,k}$ [N/mm^2]	Standard
Annealed glass (ANG)	45	SN EN 572-1
Borosilicate glass (annealed)	45	SN EN 1748-1
Heat strengthened glass (HSG)	70	SN EN 1863-1
Enameled HSG (e.g. ceramic	45	
frit)	55	
Cast HSG		
Thermally toughened glass	120	SN EN 12150-1
(TTG)	75	
Enameled HSG (e.g. ceramic frit)		
Borosilicate TTG	120	SN EN 13024-1

annealed and pre-stressed glass and includes all factors as explained below.

$$f_{g,d} = k_{mod} \cdot k_E \cdot k_V \cdot k_c \cdot \frac{f_{g,k}}{\gamma_M} \qquad (1)$$

The factors and their application criteria are defined in corresponding paragraphs to eliminate misunderstandings. Modification factor k_{mod} is used to respect the influence of load duration for annealed glass as shown in Table 3. Thermally toughened glass is usually designed with $k_{mod} = 1.0$, except for extremely short-term actions (explosion, pendulum impact). Edge finishing factor k_E is referring to edge stress and differentiates between in-plane and out-of-plane loading as well taking into account edge finishes. For laminated glass (LG) and LSG designed with the "simplified method" (as described in Sect. 0) the redundancy factor $k_V = 1.1$ can be used. The coefficient to consider the construction may be set at $k_c = 1.4$ for float glass that is solely linearly supported. The material partial factor γ_M differs between annealed glass (1.8) and thermally toughened glass types (1.5).

Table 3 Values for modification factor k_{mod} for annealed glass

Permanent	Self-weight, difference in altitude (climatic loads), traffic load	0.3
Medium	snow, climatic load	0.45
Short	Barrier person loads—crowds, maintenance load, point load accessible glass	0.75
Very short	Barrier personnel loads —normal duty, wind, earthquake	0.9
Extremely short	impact (pendulum impact, explosion)	1.8

If there are several actions in a combination, k_{mod} is determined according to the action with the shortest duration. Therefore, not only the combination of actions with the maximum stress may be relevant, also load combinations with lower stresses but also lower k_{mod} for design bending strength.

2.5 Laminated glass design

The handling of compound action, typically expressed via shear transfer (shear modulus G), of LG and LSG in structural design is often discussed in practice. In most cases or standards (SIGAB 2007), shear transfer is neglected, if it is beneficial. Full shear interaction must be considered, if it is unfavorable. On the other hand, interlayer producers made tests and offer shear modulus values for structural calculations. The SIA 2057 allows both ways, the *simplified procedure* and the *procedure considering shear transfer of interlayers* as is described below.

2.6 The simplified procedure

The simplified procedure neglects the shear transfer effect existing within LG and LSG. However, unfavorable effects of shear transfer must be considered. An unfavorable effect is e.g. if the stiffness of a LG / LSG has negative effect on stresses of another ply. This is the case especially in IGU's, where a high shear transfer of a laminated glass leads to increased stiffness and thus causes higher climate load and consequently, also higher glass stress.

In ultimate limit state (ULS) verification, shear transfer is neglected. In finite element analysis (FEA),

an extremely low shear modulus such as G = 0.0001 N/mm^2 can be used pragmatically to achieve convergency without affecting the glass stiffness and analysis results. For full shear interaction, the engineer can either use a monolithic glass ply with the sum of laminated glass ply thicknesses (full compound) or a high shear modulus G > 300 N/mm^2 [as mentioned in SJ MEPLA (2022a)].

Beside the simple and fast procedure, there are two additional provisions that are advantageous for engineering:

(a) The design stress can be increased about 10% for all glass types ($k_V = 1.1$)
(b) For service limit state (SLS), a shear modulus of $G = 0.4$ N/mm^2 can be applied for short load actions.

2.7 Procedure considering shear transfer of interlayers

Considering shear transfer is only allowed for LSG according to EN ISO 12543-2 (2011), not for LG according to EN ISO 12543-3 (2011). Application of the procedure including shear transfer may result in considerably increased design effort in engineering and should thus be applied if gains with respect to cost and construction can be achieved by the more detailed analysis: First, an appropriate calculation model, e.g. sandwich-theory based analytical approaches presented in Wölfel (1987) and Galuppi and Royer-Carfagni (2014) or either layered shell elements or volume elements in numerical analyses, must be used for the laminate. Second, the non-linear properties of the polymer/ionomer interlayer have to be readily available or need to be determined. Due to the load speed and temperature dependent material properties, polymeric and ionomer interlayers are typically modelled using viscoelastic material laws. A typical practical analysis approach is to choose the appropriate shear modulus of the interlayer for the respective load duration and temperature for each of the applied load cases. In each load combination, the respective shear modulus is thus chosen according to the leading variable action. Thus, each respective analysis run can use linear-elastic material laws. The SIA 2057 contains a table with recommended load durations and laminate temperatures for standard cases. Those must be determined for each load case.

As a qualitative example, a LSG that is accessible for maintenance work in summer and winter, may be subject to the following analysis situations:

- Winter cases:
  - Simultaneous snow and maintenance load $\gamma_G\,G_k + \gamma_Q{\cdot}P_k + \psi_{0,s}\,s_k$ or $\gamma_G\,G_k + \gamma_Q{\cdot}s_k + \psi_{0,P}\,P_k$
  - Low temperature (snow), thus higher interlayer stiffness and increased laminate stiffness $\gamma_G{\cdot}G_k + \gamma_Q{\cdot}P_k$

- Summer case:
  Maintenance load only (no snow) $\gamma_G{\cdot}G_k + \gamma_Q{\cdot}P_k$
- Higher temperature, thus lower interlayer stiffness and reduced laminated stiffness

Even though the combined snow and maintenance load in winter are higher than the sole maintenance load in the summer case, the influence of the temperature on the interlayer shear modulus could still result in higher tensile bending stress caused by the maintenance load in summer due of the reduced stiffness of the glass laminate. It is usually necessary to determine the governing situation (that causes the max. tensile glass stress) of load combinations and respective laminate stiffness due to temperature by analyzing all possible combinations.

Beside the additional work to determine the relevant combination of actions, the use of the factor $k_V = 1.0$ (and not = 1.1, as with the simplified approach) is a drawback of the detailed procedure. Application of this procedure is particularly effective in obtaining reduced, economical LSG thickness if interlayer material such as structural Polyvinylbutyral (PVB) (Fildhuth et al. 2022) (Kraus et al. 2017) or ionomer (du pont 2008) (Overend et al. 2014) is used, because these materials provide considerable shear modules even at higher temperature (Schuster 2022).

In case of structural PVB or other high performing products, this procedure can reduce LSG glass thicknesses without any safety concerns.

2.8 The four limit states concept

Similar to prCEN/TS 19100-1:2020, a four limit states concept has been established; serviceability limit state (SLS), ultimate limit state (ULS), fracture limit state (FLS) and post fracture limit state (PFLS). These states are described as principles in Sects. 4.3 to 4.6 in the SIA

2057 and complemented with restrictions and "application types" in Sect. 5 for nine typical types of glass applications, such as vertical, horizontal or barrier glazing etc.

The ULS and SLS verification according to SIA 2057 follow the same principles as prCEN/TS 19100 (future EN 19100): Stress verification with comparison of maximum principal tensile design stress determined for the glass construction via analysis with the design bending strength according to Eq. 1 for ULS. In SLS, the characteristic load combination is required to determine the glass deformation, which is compared to the reference of limit deformation from SIA 2057 or project-specific deformation limits.

Verification of safe fracture behavior (FLS) is intended to protect people from harm during or immediately after a glass failure. A suitable choice of glass buildup and support conditions contribute to this. Section 5 of SIA 2057 provides rules for supports, applicable glass types and buildup for each component. To cite an example, freely accessible glazing must be made from TTG / TTG-HST, LSG or glass with appliqued film for enhanced fracture behavior. Additional restrictions and guidance on glass and buildup choice can be found throughout the other subsections of Sect. 5 in SIA 2057, such as the obligation to use LSG for horizontal glazing (Sect. 5.3) or barrier glazing (Sect. 5.5). In certain cases, a minimum thickness of the PVB interlayer is also required. For glazing that is used as roof or floor member, reference is made to the impact and fall resistance, which must be considered project-specifically. For barrier glazing without linear supports, verification of impact loads (practical or calculated pendulum impact) is required due to the increased risk of fracture due to local stress peaks.

The PFLS is a new approach in Swiss glass design. It takes the brittle material behavior of glass into account and provides the base for the possibility to analyze the residual capacity of glass elements/constructions in partial or entire fractured conditions. Therefore, the SIA 2057 defines fracture states for glass components in respect to their application. PFLS verification for fractured glass is considered being an accidental design situation with accidental combination of actions according to SIA 260. Verification can be made by calculation or testing for partially fractured glass elements (e.g. one ply a LSG broken) and must be made by testing for fully fractured state (e.g. all plies of a LSG broken).

Detailed description follows in Sect. 3 of this article to highlight this particular topic.

## 3 Post fracture limit state verification

3.1 Fracture states

SIA 2057 basically requires to perform verification of all four limit states; particular rules and exceptions for each glass construction type are provided in Sect. 5 of the specification. Therefore, as described above, nine different glass application types (vertical / horizontal glazing, IGU, barrier glazing, accessible glazing, glazing subjected to the public or vehicles, compression- or bending-loaded glass members) are defined at the start of Sect. 5 and then all limit state verifications that have to be checked are described in detail for each application type in the subsections 5.2 to 5.10. In most cases, all four limit states need to be addressed in design verification, including the partially or fully fractured state.

Section 4.6 defines a range of fracture states classified into five steps NB0 to NB4 (NB = "Nachweise im Bruchzustand", fracture state verification). A distinction is made between partially fractured (NB1, NB3A, NB3B) and completely fractured (NB2, NB4) states as well as without load (NB1, NB2) and with additional load (NB3A, NB3B, NB4). The full description of these classes is the following (see also Fig. 2):

- NB0: no additional PFLS verification necessary.
- NB1: Residual load bearing capacity under dead load in partially fractured condition.
- NB2: Residual load bearing capacity under dead load in fully fractured condition.
- NB3: Residual load bearing capacity for accidental load combinations and partially fractured state. NB3 distinguishes the sub-states NB3A = one fractured ply and NB3B = two fractured plies.
- NB4: Residual load bearing capacity for accidental load combinations and fully fractured state.

Even if the fractured glass plies are shown as the lower plies in Fig. 2, basically any ply can be assumed broken in the verification process. The design engineer has to decide which glass ply / plies have to be considered as fractured with respect to the installation situation and which situation of fractured plies delivers the most severe design situation.

Fig. 2 Schematic representation of fracture states for PFLS for a LSG shown for the example of three glass plies, small triangles indicate a fractured ply
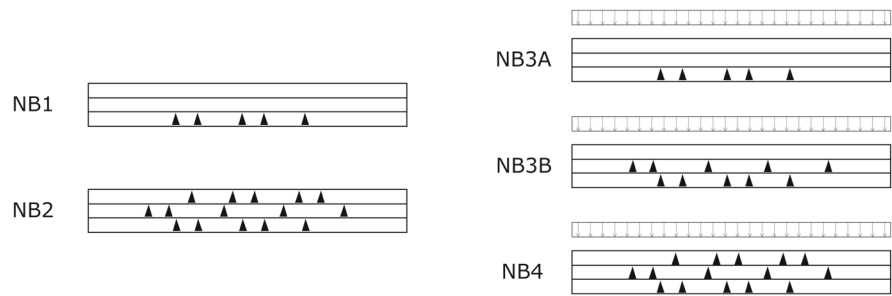
3.2 Design verification PFLS

The PFLS verification distinguishes two cases:

- Residual load bearing capacity for partially fractured state: A minimum of one ply of an LSG or IGU is still intact. The design verification can be made by calculation or through testing.
- Residual load bearing capacity for fully fractured state: All glass plies of a LSG or IGU are broken. Design verification is performed by testing only.

In both cases, PFLS situations are accidental situations according to SIA 2057 and SIA 260 (SIA 2013). In the SIA 2057, the accidental leading effect is defined as $A_d = \psi_{1,1} \bullet Q_{k,1}$, which leads to the load combination in Eq. 2 below.

$$E_d = G_k + \overbrace{\psi_{1,1} \cdot Q_{k,1}}^{Ad} + \sum \psi_{2,i} \cdot Q_{k,i} \qquad (2)$$

For the partially fractured state, where at least one ply must remain intact, a calculation approach to verify PFLS is proposed to avoid cost-intensive, test-based verification. For this approach, the loads from the accidental load combinations are applied to the remaining intact glass ply. The design bending strength (including material safety factor) remains the same as in ULS verification. The broken plies are not taken into consideration. Thus, this verification approach is conservative.

As stated above, practical tests can be carried out for verifying the partially fractured state and must be applied for the completely fractured state. In addition, it is possible to replace the test for the partially fractured condition by testing the fully fractured state using the same loads.

An example of this is a LSG with three glass plies with the requirement NB3B (Fig. 2, partially fractured state with two plies broken), where two options A) and

B) are possible for the verification of the partially fractured state (as per Sect. 3.2 above, first bullet point):

(A) Mathematical verification in partial fractured state: Two plies broken, one ply intact: Mathematical verification of the remaining ply of glass with the load of the governing accidental load combination according to Eq. 2.
(B) Test-based verification of the completely fractured state for a LSG with two plies: A two-ply LSG, corresponding to the two plies considered broken in condition NB3B, is tested with the load of the governing accidental load combination according to Eq. 2.

The project engineers must decide on the option to apply. In addition, the SIA 2057 also draws the engineer's attention to the fact that it may not only be necessary to consider the specified load combination. It may also be necessary to step on roofs (skylights) when clearing snow. According to Eq. 2, the maintenance loads on roofs (category H according to SIA 261) are not considered due to the ψ-factor being always 0. If it is not possible to inspect the glazing before entering, this should also be considered in the PFLS verification.

Generally, the following verifications are required for the different glass application types according to Sect. 5 of the SIA 2057 as shown in Table 4 hereafter. Please note, that Table 4 only provides a simplified summary of the verifications to be performed as per Sect. 5 of SIA 2057, where the fracture state to be checked is always shown depending on the three conditions given in the bullet points below:

- Glass application type (nine types)
- Usage category of the building as per SIA 260 (A to D and H)
- Boundary conditions of the built-in glazing, such as four-side support etc.

Table 4 Construction type and respective fracture states

Glass application type	Fracture states to be verified
Vertical glazing	NB0 for all usage categories and boundary conditions
Horizontal glazing	NB0 /NB3B
	(Depending on aspect ratio length / width and edge supports)
IGU	As given by the category of the usage of the IGU (e.g. as vertical glazing)
Barrier glazing (fall prevention)	NB0, NB3A
	(depending on the barrier type group and the usage category)
Glazing accessible for maintenance (category H according to SIA 261)	NB3A NB3B
	(Depending on aspect ratio length / width and edge supports)
Accessible glazing (categories A to D, according to SIA 261)	Generally NB3B
	For linear support and span < 350 mm, NB3A applies
Glazing accessible for vehicles	Minimum requirement: NB3B
Compression-loaded glass elements (buckling)	NB2, if an alternative load path exits in case of glass failure
	Otherwise: NB3B
Glass elements subjected to bending (lateral torsional buckling)	NB2, if an alternative load path exits in case of glass failure
	Otherwise: NB3B

The following Section of the present article provides a design example to show the application of the procedure outlined in the SIA 2057.

4 Design example

A category H roof glazing having dimensions of 1.6 m × 0.7 m (snow and maintenance load, accessibility for maintenance only) made of LSG composed of 2 × 8 mm annealed glass, as it could be used in, e.g., factory roofs, shall serve as a calculation example to demonstrate how LSG and PFLS verifications are handled in SIA 2057. Schematic and structural sketches are shown in Fig. 3. The actions, their γ or ψ factors and

modification factors k_{mod} can be obtained from Table 5.

As mentioned before in Sect. 0, in case of LSG the structural calculation can be made with the simplified procedure or the procedure considering shear transfer of interlayers. In the following subchapters, both calculations are shown to demonstrate their strengths and weaknesses.

The example meets all requirements of SIA 2057 for roof or overhead glazing:

- 0.76 mm PVB interlayer.
- Difference between glass plies less than factor 1:1.7.
- Four-sided linear support: $k_c = 1.4$ can be applied.
- For PFLS the fracture state NB3A must be verified (glazing accessible for maintenance, aspect ratio < 3: 1, four-sided linear support refer to Table 4), which means one glass ply is omitted in the accidental load combination.

The following calculations for σ_{max} are performed with SJ MEPLA glass design software (SJ MEPLA 2022b). Beside the general implemented basics and the parameters in this document, the calculations are based on a 15 mm mesh after checking of the mesh density influence and the analysis is conducted geometrically non-linear.

## 4.1 ULS verification with with simplified procedure

As derived in Sect. 0 and Eq. 1, the design bending strength for this example is based on Eq. 3 below and summarized in Table 6. Therein the factors are fixed as:

- $k_E = 1.0$, because there is no edge under tensile stress,
- $k_c = 1.4$ for annealed glass that is only linearly supported,
- $k_V = 1.1$ for laminated glass design with the simplified procedure, and
- $\gamma_M = 1.8$ for annealed glass.

$$f_{g,d} = k_{mod} \cdot 1 \cdot 1.1 \cdot 1.4 \cdot \frac{45 \text{ MPa}}{1.8} \qquad (3)$$

Factor k_{mod} is a parameter depending on the load durations within a load combination and, therefore, listed for each of the potential combinations in Table 6. Regarding load combinations with $k_{mod} = 0.75$, the number of load case combination analyses can be

Fig. 3 Calculation example:
a maintenance accessible
glazing sketch and
b structural sketch

(a)   **(b)**
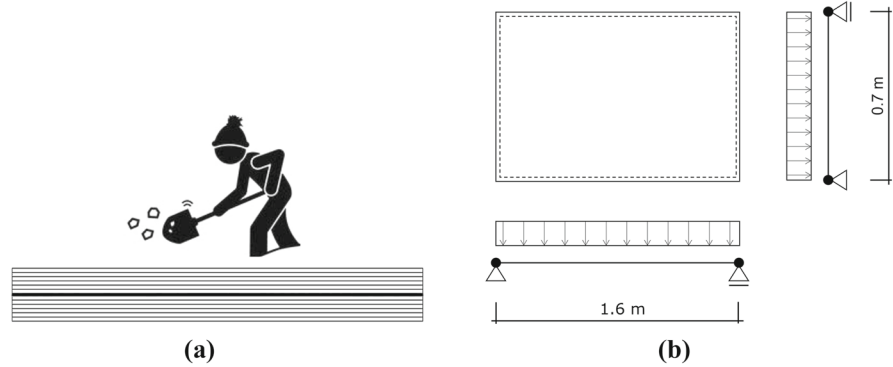
Table 5 Actions and factors according to SIA 2057 (2021), SIA 260 (2013) and SIA 261 (2020)

	Q_k/q_k	γ	ψ_0	ψ_1	ψ_2	k_{mod}
Dead load G_k		1.35	–	–	–	0.3
Snow $q_{s,k}$	1.3 kN/m^2	1.5	0.88	0.5	0	0.45
Live load $q_{l,k}$	0.4 kN/m^2	1.5	0	0	0	0.75
Point load $Q_{p,k}$	1.0 kN	1.5	0	0	0	0.75

Table 6 Load combinations, k_{mod} factor, design resistance $f_{g,d}$ and maximum design stress σ_{max} for calculation with the simplified procedure neglecting shear transfer in ULS

Nr	Load combination ULS	k_{mod} [–]	$f_{g,d}$ [MPa]	G [MPa]	σ_{max} [MPa]
1	$E_d = \gamma_G \cdot G_k$	0.3	11.55	–	1.4
2	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k}$	0.45	17.33	–	6.2
3	~~$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k} + \psi_0 \cdot q_{l,k}$~~				
4	~~$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k} + \psi_0 \cdot Q_{p,k}$~~				
5	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{l,k} + \psi_0 \cdot q_{S,k}$	0.75	28.9	–	5.7
6	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot Q_{p,k} + \psi_0 \cdot q_{S,k}$	0.75	28.9	–	29.0
7	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{l,k}$	0.75	28.9	–	2.9
8	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot Q_{p,k}$	0.75	28.9	–	26.2

reduced to the ones with the highest load. Especially combinations 3 and 4 are obsolete, because ψ for live load $q_{l,k}$ and point load $Q_{p,k}$ is equal to 0 and would thus deliver the same maximum stresses as load case combination 2 this is why these combinations are cancelled out in Table 6.

The far-right column of Table 6 shows the calculated maximum design stress σ_{max}, where load combination 6 is slightly exceeding the ultimate stress limit.

For SLS, the SIA 2057 offers the opportunity to use $G = 0.4$ N/mm^2 for short load actions, which reduces the deformation. In this example, deflection

thus reduces from 1.9 mm to 1.6 mm, both being below the reference of $L/100 = 7$ mm for horizontal glazing and thus not being governing in the present case.

4.2 ULS verification considering shear transfer of interlayers

Alternatively, the structural safety verification can be made considering shear transfer of interlayers. In this case, standard PVB is applied. This procedure makes the glass design more complex. First, the 10% resistance increase of LSG for design bending strength is

not applicable, see $k_V = 1.0$ in Eq. 4. Second, for each load combination the specific PVB properties depending on load duration and temperature must be known and applied.

$$f_{g,d} = k_{mod} \cdot 1 \cdot 1.0 \cdot 1.4 \cdot \frac{45 \text{ MPa}}{1.8} \qquad (4)$$

The Table 13 in Annex A of the SIA 2057 gives representative load durations and temperatures, depending on layer structure and installation situation. In this case, 10 min at 50 °C are given for horizontal glazing accessible for maintenance. Snow or maintenance access in wintertime is not specially mentioned. In case of snow, 0 °C is chosen a suitable temperature. The load duration of snow is depending on the location, in Swiss midland a load duration of snow is, based on experience, about one to two months and one month is used in the present case. For the LSG glazing considered here, the PVB properties are, as an example, taken from online accessible datasheets (Saflex 2020b) and (Saflex 2020a) for clear PVB as follows:

Dead load	Permanent (25 years)	$G = 0.0$ N/mm^2
Snow	1 month, 0 °C	$G = 0.7$ N/mm^2
Maintenance load	10 min, 50 °C (summer)	$G = 0.13$ N/mm^2
	10 min, 10 °C* (winter)	$G = 5.0$ N/mm^2
Maintenance point load	10 min, 50 °C (summer)	$G = 0.13$ N/mm^2
	10 min, 10 °C* (winter)	$G = 5.0$ N/mm^2

*Data for 0 °C and 10 min is not available, thus, 10 °C is used instead

Most interlayer manufacturers provide comparable datasheets with time- and temperature-dependent data. Apart from the example product cited above, such information can also be found in Pujol (2020) or Kuraray (2023), just to name a few.

In addition, more attention must be paid to the load combination, their load duration and temperature. Especially the maintenance point load, which can occur both in winter or in summer. That means, a reduction of load combinations to save analysis time must be decided carefully. In Table 7 all the load combinations and parameters as well as the maximum design stresses $\sigma_{\max}$ are listed. Even if the influence of shear transfer is low, all the load combinations fulfill the ULS with the lower design bending strength ($k_V = 1.0$).

For SLS, the same G values can be used which reduces maximum deformation to 1.37 mm, which also meets the standard criteria of $L/100 = 7$ mm. The maximum design stress determined is 25.5 N/mm^2, whereas the simplified procedure results in a maximum design stress of 29.0 N/mm^2.

4.3 PFLS verification

As described in Sect. 3.2 of this article, classification NB3A means that one glass ply is fractured. The dead load of the fractured ply must be applied, therefore the dead load of the remaining single glass ply G_k is multiplied with factor 2.

In addition, regardless of the questions if the intact LSG is designed with the simplified procedure or with the procedure considering shear transfer of interlayers, the remaining ply is a single ply. This also means that k_V is set to 1.0 for a single glass ply.

Table 8 shows the remaining load combinations one and two following the SIA 260 load combination rules. Combination E1 and E2 are "Extra load combinations" provided the case that someone does not see the fractured glass and walks on the glazing for maintenance or snow clearing work in winter scenario.

Depending on the installation situation, the PFLS verification is fulfilled or not. There is no final rule to rate this, it is the responsibility of the planner and the engineer to determine the hazardous situation.

Note: If the intact LSG was made of three glass plies, the verification for the remaining two-ply LSG in NB3A PFLS changes:

- Using the simplified procedure, the remaining two-ply LSG is still a LSG, and $k_V = 1.1$ can still be used;
- While considering shear transfer of interlayers is still applicable for the remaining two-ply LSG.

Table 7 Load case combinations, k_{mod} factor, design resistance and maximum stress for calculation with considering shear transfer of interlayers in ULS

Nr	Load combination ULS	k_{mod} [−]	$f_{g,d}$ [N/mm^2]	G [N/mm^2]	σ_{max} [N/mm^2]
1	$E_d = \gamma_G \cdot G_k$	0.3	10.5	0.0	1.4
2	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k}$	0.45	15.75	0.7	5.0
3	~~$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k} + \psi_0 \cdot q_{l,k}$~~				
4	~~$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{S,k} + \psi_0 \cdot Q_{p,k}$~~				
5	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{l,k} + \psi_0 \cdot q_{S,k}$	0.75	26.25	5.0	3.3
6	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot Q_{p,k} + \psi_0 \cdot q_{S,k}$	0.75	26.25	5.0	21.3
7	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot q_{l,k}$	0.75	26.25	0.13	2.7
8	$E_d = \gamma_G \cdot G_k + \gamma_Q \cdot Q_{p,k}$	0.75	26.25	0.13	25.5

Table 8 Load case combinations, k_{mod} factor, design resistance and maximum stress for PFLS calculation

Nr	Load combination	k_{mod} [−]	$f_{g,d}$ [N/mm^2]	G [N/mm^2]	σ_{max} [N/mm^2]
1	$E_d = 2 \cdot G_k$	0.3	10.5	–	2.0
2	$E_d = 2 \cdot G_k + \psi_{1,s} \cdot q_{S,k}$	0.45	15.75	–	5.2
E1	$E_d = 2 \cdot G_k + 1 \cdot Q_{p,k}$	0.75	26.25	–	35.3
E2	$E_d = 2 \cdot G_k + 1 \cdot Q_{p,k} + \psi_{1,s} \cdot q_{S,k}$	0.75	26.25	–	38.5

5 Conclusion and outlook

The Technical Specification SIA 2057 Glasbau (glass construction) is developed to fill the existing gap regarding national glass design rules in Switzerland. Furthermore, with respect to the future implementation of EN 19100 in Switzerland and the successive future abandon of Swiss codes, the principles and procedures of SIA 2057 already follow the principles of prCEN/TS 19100. SIA 2057 thus both contains the EN design principles as well as the SIA principles aiming at providing design guidelines without obstructing design freedom. Besides clear and comprehensive requirements, the project engineer can thus also use alternative and innovative verification methods.

The SIA 2057 focusses on critical points in glass design and introduces a four-limit state concept comprising SLS, ULS, the fracture limit state (FLS) and the post fracture limit state (PFLS) to ensure safe and robust glass design. On one hand, the new PFLS verifications is additional work and the application in practice takes time, but allows for more economic and specific glass design. On the other hand, the SIA 2057 gives

alternative verification opportunities to encourage new or innovative glass products.

With the new PFLS verification, the safety of critical glass members is regarded primarily, which are mainly barrier, vertical, roof and floor glazing. For those components a residual load bearing capacity must be provided in case of accidental failure to protect people. This verification can be made with calculation or tests for PLFS. Nevertheless, the PFLS with its fracture states can also be used as additional safety verification. This means due to the comprehensive definition, also higher requirements are clearly defined.

The ability to take shear transfer into account gives further design options to the engineer. As shown in the example, the effort involved in considering the shear transfer of the interlayer is higher but can lead to more efficiently designed glass structures. Especially when structural PVB or high temperature-resistant interlayers such as ionomers are used. Even with this more efficient glass design, the PFLS system guarantees safety in the event of accidental fracture.

The Technical Specification SIA 2057 is not yet a standard. But a technical guideline with the typical content and principles of a standard. The period of validity is limited to five years, after which a review is carried out. It is not yet clear whether the SIA 2057 will become a Swiss SIA standard or will be replaced by the EN 19100 or partially act as its national annex. This depends on the future introduction of EN 19100 and the timeline to replace Swiss standards by Eurocodes.

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