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Ten Years of Stiff PVB: An Overview of Developments and Current Status

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Abstract

Around ten years ago, reduced plasticizer content poly(vinyl butyral) (PVB) interlayer types were introduced to the laminated glass market for use in general construction. The main purpose of these interlayers is to reduce the glass thickness or enable larger glazing spans. In these stiff PVB types, the plasticizer level is reduced to around 17 weight %, as compared to around 27 weight % for conventional PVB types. Although it was known at the time that these formulations can meet safety requirements for laminated glass, the options for use in structural design of laminated glass were less apparent. This was due to a lack of suitable standards and/or national approvals on one hand, and a lack of broader set of performance data on the other hand. Meanwhile, many of these gaps have been addressed, and performance data from various suppliers have been on a converging path, as progress in standardization was made and best-practices emerged. In addition, interest in the use of stiff interlayers in general has recently intensified, as they can improve carbon footprint of laminated glass and facades. This article aims to cover these developments, as well as providing complimentary information on some aspects. Eventually, stiff PVB's have become a viable interlayer choice in suitable laminated glass applications, supported by a substantial amount of performance data from multiple suppliers. Drivers for the use of this material category have changed from merely economic to supporting sustainability targets through carbon footprint reduction.

Keywords

Stiff PVB, Laminated Glass, Review

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1. Introduction

Reduced plasticizer level PVB formulations have been used historically in niche applications where high adhesion and resistance to deflection were a key aspect of performance, e.g. for the adhesion of spall shield layers in bullet resistant glass or train window applications, and improved infill retention as compared to conventional PVB types in specific applications. These grades were the basis for products more adapted for generic use in the laminated glass market as they could be adapted with relative ease for this use by e.g., thickness adjustment. In addition, with development of prEN 16612:2013 (and its precursors) it became clear that these products would be allowed to contribute to the effective thickness of a laminated glass by shear transfer in structural design in Europe. The basic rheological differences between conventional PVB (27 % wt. % plasticizer) and stiff PVB (17 % wt. % plasticizer) are illustrated in Figure 1 by a plot of the shear storage modulus (G'), the loss modulus (G") and tan δ. The latter reflects the ability of the PVB interlayers to absorb energy, which is clearly important for an interlayer intended for use in laminated safety glass. There are several noteworthy elements in Figure 1. The overall shape of the curves is similar, with each curve for stiff PVB moved approximately to the right by about 15 ^{o}C. The peak of the tan δ indicates the position of the dynamic glass transition point of the materials, at around 28 ^{o}C for conventional PVB and around 43 ^{o}C for stiff PVB. This would correspond to the performance optimum for properties where energy loss is key e.g., impact performance and acoustic performance, as explored in Novotný & Poot (2016). The plateau values in both the elastic regime (low temperatures) and viscous regime (high temperatures) are slightly higher for the stiff PVB type, a reflection of the higher polymer content of the latter.

The basic rheological properties of Figure 1 are reflected in basic performance characteristics as compiled in Table 1. Whereas stiff PVB's have a clear potential structural design benefit at higher temperatures and/or longer durations over conventional PVB, acoustic and impact performance at room temperature is slightly reduced as compared to conventional PVB. Measured adhesion is typically higher for stiff PVB types than for conventional PVB types, but care must be taken in the interpretation. In many cases, the outcome of the adhesion measurement reflects both surface adhesive strength and bulk rheology. For a proper comparison of surface adhesive strength, experiments at different temperatures would be required.

To use a new interlayer material successfully for the structural design of glass, several elements need to be in place. Applicable standards and regulations need to allow the use of interlayer properties in glass design, either directly or indirectly. In this area, much progress has been made in the last ten years. It is important to cover these developments as they allow to understand the current application space for stiff PVB interlayers. Impact performance of laminated glass is key for a product to be qualified as laminated safety glass. Besides impact performance, post-breakage performance of laminated glass is another important, yet invisible safety feature. Some durability characteristics of laminated safety glass are required by standard, but durability of adhesion, mechanical properties and edge stability are not. A good insight into these aspects can not only instill confidence in a product, but also provide additional drivers for specification. Finally, the mechanical interlayer properties used for design must have been established reliably and without ambiguity. All these elements will be covered in paragraphs below.

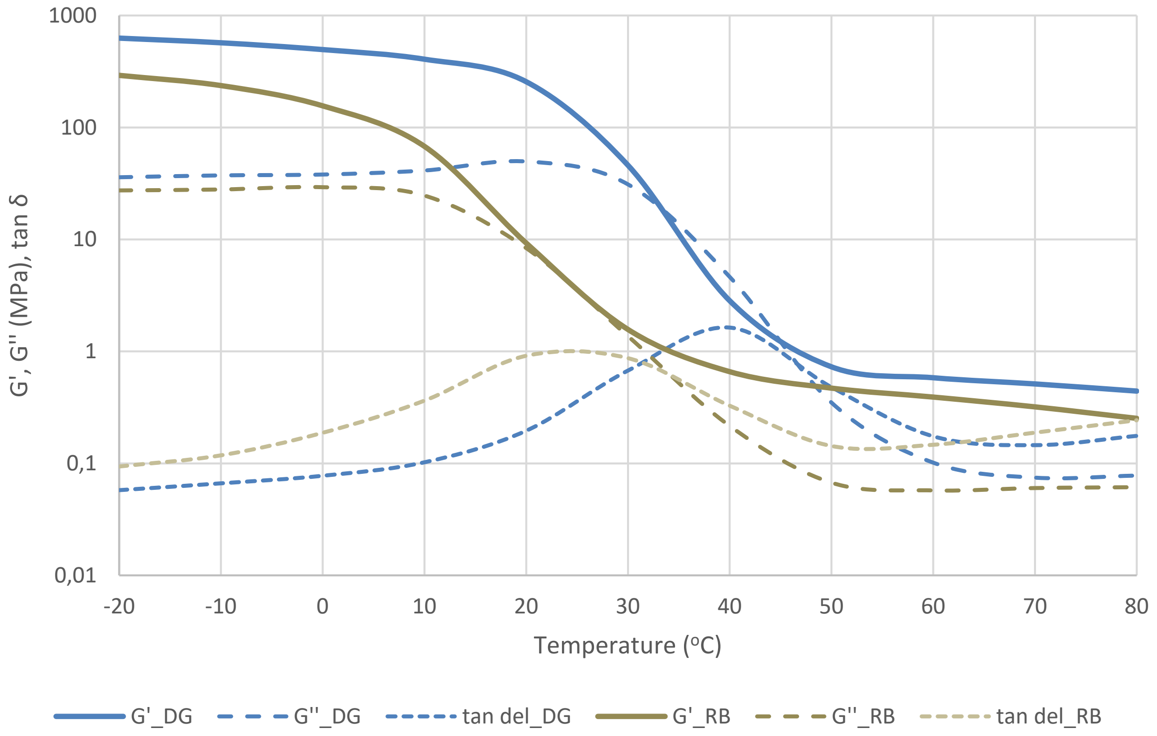

Fig. 1: Generic DMTA graphs at 1 Hz of the shear storage (G’) and loss modulus G”
as well as tan δ for a conventional (grey lines) and stiff PVB type (blue lines).

Table 1: Typical properties of conventional and stiff PVB interlayer as relevant to laminated glass,
as measured on either interlayer film or laminated glass comprising the film.

Test name/quantity	Reference standard	Unit or performance level	Conventional PVB	Stiff PVB
			Film property	
Tensile, elongation at break	EN ISO 527-3*	%	270	196
Tensile stress at break	EN ISO 527-3*	MPa	23	33
Shear relaxation modulus	EN 16613	MPa	0.43 (5 min, 30 °C)	2.2 (5 min, 30 °C)
			1.0 (1 month, 0 °C)	105 (1 month, 0 °C)
			Laminated glass property	
Soft body impact	EN 12600	1B1	33.2 Pass	33.2 Pass
Ball drop impact	EN 356	P2A	44.2 Pass	44.4 Pass
Acoustic loss factor	ISO 16940	-	0.050	0.036
Acoustic, Rw	EN ISO 10140	dB	33 (33.2)	32 (33.2)
			37 (66.4)	36 (66.4)
Adhesion, compressive shear	NA	MPa	10 - 15	15 - 20
Adhesion, torsion	NA	MPa	4 - 6	7 – 9**

*50 mm/min, 23 °C, 50 % humidity

**sample failure through glass failure, values can be considered as minimum values

2. Standards and regulatory developments

This In a European CEN standardization context, two technical committees (TC) have concerned themselves with providing guidance for the evaluation of glass structures:

- CEN/TC129/WG8 Glass in Building – Mechanical Strength
- CEN/TC/250/SC11/(WG1) Structural Eurocodes – Design of Glass Structures

In 2013, prEN 16612 *Determination of the load resistance of glass panes by calculation and testing* was just submitted for enquiry by TC129/WG8 at the time of launch of the first stiff PVB interlayer. In parallel, prEN 16613 *Determination of interlayer mechanical properties* was published. In addition, early in 2014, CEN TC250/WG3 published *Guidance for European Structural Design of Glass Components* (Feldmann et al., 2014). CEN TC250/WG3 later moved to formal subcommittee status (SC11) preparing Technical Specification documents TS 19100 1-4 (2021), and a working group (WG1) was added to convert the first three parts into draft European standards (prEN 19100 1-3; likely 2024). For the purposes of this document, it is described how these documents deal with interlayer properties in glass design.

2.1. EN 16612 Determination of the lateral load resistance of glass panes by calculation

In prEN 16612:2013 it was recognized that in cases where shear stress is developed in laminated glass parallel with the interlayer, the interlayer can be considered as having some shear resistance. The viscoelastic properties of the interlayer as determined to prEN 16613:2013 could be used in a suitable engineering formula or calculation method to evaluate the resistance to bending of laminated glass. Alternatively, the effective thickness of laminated glass could be calculated based on default shear transfer coefficients ω, assigned to specific load scenarios for four different stiffness families of interlayers. These stiffness families were defined per load scenario in prEN 16613:2013 based on the interlayer elastic modulus. Unrelated to the methodology of dealing with interlayers, prEN16612:2013 was never accepted for publication. A significantly changed version was finally published as EN 16612 in 2019, with a scope adopted to fit the Eurocode framework.

The stiffness family approach has consistently met with critique, as it lacks a scientific foundation. In addition, the relatively simple approach to calculating the effective thickness is inaccurate. This is largely compensated for by the conservative values of ω as listed in Table 2. A higher level of shear transfer would almost always be effectively achieved in direct finite elemental calculations using the actual modulus, potentially resulting in thinner or larger glass structures. In that sense the stiffness family approach results in a conservative outcome and thus can still be acceptable.

Technically, EN 16613 as it stands has considerable technical shortcomings, to the point that TC250/SC11 deemed the results not reliable enough to be used in structural design in conjunction with the Eurocode *Design of Glas Structures* under development. Meanwhile, a revised standard has been prepared by TC129/WG3, which is expected to go to enquiry in early spring of 2024. Changes include options for primary data collection, improved guidance on data processing and a validation step with results obtained on not only the interlayer but also on laminated glass with that interlayer. In contrast to EN 16613:2019, prEN 16613:2024 provides information to calculate coupling factors η based on the interlayer shear relaxation modulus G(t) for use in the more accurate effective enhanced effective thickness (EET) method. This also prevents any discussion on modulus values that are around the thresholds set in current EN 16613, leading to just achieving or not achieving a certain stiffness family classification.

Table 2: Stiffness family classification of stiff PVB to EN 16612/EN1663.

Load scenario	Duration	Maximum Temp. (°C)	EN 16613 SF2 criterion E(t) (Mpa)	SF2 default ω EN 16612	SF Stiff PVB
Wind gust load (Mediterranean areas)	3 s	35	> 20	0.5	1 or 2*
Wind gust load (other areas)	3 s	20	>100	0.7	2
Wind storm load (Mediterranean areas)	10 min	35	>1	0.1	2
Wind storm load (other areas)	10 min	20	> 20	0.5	2
Balustrade loads_ no crowds	30 s	30	> 20	0.5	2
Balustrade loads_ crowds	5 min	30	> 10	0.3	1 or 2*
Maintenance loads	30 min	40	>1	0.1	2
Snow load external canopy/unheated	3 weeks	0	> 10	0.3	2
Snow load external roofs of heated buildings	5 days	20	>1	0.1	2
Cavity pressure variation IGU: summer	6 hours	40	>1	0.1	2
Cavity pressure variation IGU: winter	12 hours	20	> 10	0.3	1 or 2*

*Classification may vary by source, consult supplier for specific type

In general, more accurate results are obtained working with modulus values obtained directly as provided by either the producers or in national approvals, regardless of if a finite element model (FEM) or EET method is used. More details are provided in the section on mechanical properties. It is expected that the interlayer modulus values based on the revised methodology in the standard will be accepted by TC250/SC11 for use with prEN 19100 1-3.

2.2. Eurocode prEN 19100 Design of Glass Structures

Developments in the future Eurocode Design of Glass Structures have come a long way since 2014, and it is likely that the first formal draft documents will be sent for enquiry this year as prEN 19100 parts 1-3. A precursor version was published as Technical Specification TS 19100, parts 1-3 in 2021. For the purposes of this document, only the paragraphs that deal with interlayer properties are briefly covered, as this will determine the relevance of stiff PVB types going forward. PrEN 19100, like EN 16612, recognizes that for laminated glass the stresses and deformations also depend on the shear modulus of the interlayer. Three levels of working with interlayer properties are provided:

- Level 1: If the interlayer properties are favorable, the shear interaction of the interlayer is ignored. If the effect of shear coupling is unfavorable, the glass is considered as monolithic based on the sum of the thickness of all glass constituent plies, essentially assuming near complete coupling. This approach does not require knowledge of interlayer shear modulus as a function of temperature and load duration.
- Level 2: use of analytical models to model the glass. The validated model provided is the EET method (see TS 19100-2 Annex A), to which prEN 16613:2024 will be aligned as well.
- Level 3: Numerical methods

Both Level 2 and 3 require the value of interlayer shear modulus used in modelling to be chosen with regard to the duration of the load and the temperature at which the load occurs. Such data are available as either specific values for certain load scenarios, tabular overviews of how the modulus varies with time and temperature or models e.g., in the form of a Prony series fit to a Maxwell Modell. Examples for all these formats are present in the national documents covered below. PrEN 19100-1 is not prescriptive in which level of interlayer modelling will be used in the membership states. This is Nationally Determined Parameter (NDP) that can be set by each of the countries in a National Annex.

2.3. National regulations and standards

National regulations and standards are only covered for countries where explicit guidance for use of stiff PVB's is available, either in the glass design standard or national approval type documents, in order of the availability of this guidance. This is the case in Norway, Germany, France and the Netherlands, presented here in order of initial availability. Other countries reference producer data directly if measured to EN 16613 or provide no guidance at all.

Norwegian standard NS 3510: 2015: *Safety glass in construction works - Requirements for design and classes in various application areas* was the first example of a national regulation that included stiff PVB types as specific interlayer category. It differentiates between interlayers (standard PVB, stiff PVB and ionoplast interlayers) in the design of certain glass structures such as cantilevered balustrades, point-fixed balustrades, and two-side supported partition walls. In addition, the modulus assumptions as applicable in Norway for stiff PVB were also listed, as compared to conventional PVB in Table 3.

Table 3: Design modulus values of conventional and stiff PVB in Norway to NS 3510.

Load scenario	Duration	Maximum Temperature (°C)	Standard PVB Modulus G(t) (MPa)	Stiff PVB Modulus G(t) (MPa)
Wind loads	3-5 s	20	3.3	33
Snow loads – unheated	3 months	0	0.4	3.3
Snow loads – heated	1 week	20	0	0.4
Live loads – internal	30 s	30	0.4	8.0
Live loads – internal crowds	30s	30	0.4	1.5
Live loads – external	5 min	35	0	1.0

In some cases, the values seem derived from a threshold value in EN 16613 for stiffness family 3 (at the time, currently stiffness family 2) e.g., a G value of 33 MPa would correspond to an E modulus value of 100 MPa approximately. In other cases, the values seem derived from supplier information. Either way, there is a basis to use modulus values for stiff PVB's in glass design in Norway. The values for wind loads, snow loads (unheated surfaces) and internal live loads are high enough to provide substantial benefits in glass design.

In Germany, use of interlayer material properties in glass design to DIN 18008 is generally not allowed, and limit state approach is used (cf. "Level 1" in paragraph on prEN 19100-1). Up to 2016 national approvals (allgemeine bauaufsichtliche Zulassungen or abZ's) could be granted to interlayer materials based on an extensive characterization file with expert review that provided design modulus values. After 2016, no national approvals for interlayer materials were granted anymore. Instead, national approvals for a construction method with glazing comprising a specific interlayer material could be granted, now called allgemeine Bauartgenehmigung (aBG). In 2013, no German approvals for stiff PVB materials were available, but currently three such approvals for stiff PVB types are available and a selection of the available design modulus values are compared in Table 4.

Table 4: Design modulus values of stiff PVB in Germany according to various national approvals.

Load scenario	Duration	Maximum Temperature	G(t) (MPa) to aBG Z-70.3-254[1]	G(t) (MPa) to aBG Z-70.3-277[2]	G(t) (MPa) to aBG Z-70.3-278[3]
Wind loads	German climate		10	9	7
Snow load - unheated	30 days	0	130	86	100
Snow load heated	30 days	23	0.7	0.6	0.6
Live load - internal and external	1 hour	30*	0.7	1.2	1.2

*For external loads, different values for higher temperatures are available

1) Verglasungen aus Verbund-Sicherheitsglas mit der Verbundfolie SAFLEX DG mit Schubverbund (2023 revision)

2) Verglasungen aus Verbund-Sicherheitsglas mit EVERLAM LAM72T für die Anwendung nach DIN 18008 (2022)

3) Verglasungen aus Verbund-Sicherheitsglas aus Trosifol® Extra Stiff B230 PVB mit Schubverbund für die Anwendung nach DIN 18008 (2022)

The values for wind loads are derived from a matrix of modulus values at different temperatures and durations as applicable in Germany based on German climate data. Therefore, no particular load scenario is provided with wind loads. The assumption on the load duration of live loads is very conservative as compared to what is usual in other countries. It is a clear that on a biaxial logarithmic scale, which is usually applied for interlayer modulus values, the similarities are much larger than the differences for the values listed in Table 4. Even on absolute scale the differences are relatively limited and will rarely lead to a change in glass design between one stiff PVB type and the next. The values for wind loads and snow loads (unheated surfaces) are high enough to provide substantial benefits in glass design.

All three German approvals contain a material model for the particular stiff PVB used, so the properties for any different load scenarios can be calculated as well. The material model has the form of a 10 element Prony series in combination with a polynomial shift function. This allows for a neutral comparison of the properties of stiff PVB materials, as well as a comparison with current producer data – all under the assumption that the underlying methodology used was similar. It seems plausible that this is the case, as there is large overlap in the academics and experts providing the base data for the German approvals and those participating to the revision of prEN 16613 in TC129/WG3. This theme will be further explored in the section on mechanical properties.

Use of interlayer material properties in France is a non-regulated area, and therefore glass design that use interlayer material properties are only accepted by the authorities based on a French national approval (in this case Document Technique d'Application – or DTA). This document is issued by an expert group under guidance of the national Center for building science and technology (Centre Scientifique et Technique du Bâtiment, or CSTB). In addition, Technical Guidance 3181 *Durability of laminated glass in construction works* specifies that non-traditional interlayers, including rigid PVB types, have a DTA approval. Only one such approval is available for a stiff PVB type at the time of writing. An overview of the applicable modulus values and shear transfer coefficients ω is provided in Table 5.

Table 5: Design modulus values of stiff PVB in France to National Approval DTA 6/22-2437_V1 for Saflex Structural DG41 XC.

Load scenario	G(t) (MPa)	ω
Wind loads	8	0.5
Snow loads – unheated	20	0.5
Snow loads – heated	1	0.2
Cavity pressure – winter (exterior pane)	20	0.4
Cavity pressure – winter (interior pane)	4	0.3
Cavity pressure summer up to 40 °C (deflection)	0.3	0

No specific load scenarios are provided for any of these values, although perhaps some inspiration can be found in EN 16612. Note that the generic value for wind loads is similar to the value for the same product in Germany (France: 8 MPa; Germany 10 MPa), even if the background may be very different. The shear coefficients ω are to be used in the calculation method of EN 16612 Annex D, but the values are different from the values in Table 2 for a Stiffness family 2 interlayer.

Dutch glass design standard NEN 2608 is unique from an interlayer perspective, as it provides material models for different interlayer categories in general that can be used to derive the relevant interlayer modulus for design. These models are similar to the models provided in the German national approvals (Prony series), except that temperature shift function is a WLF equation, rather than a polynomial shift function. prNEN 2608:2024 is expected to comprise a stiff PVB model for the first time. It is slightly conservative as compared to the material models in the German approvals. Since this standard is not distributed for enquiry yet, no values are presented here.

In conclusion, at the time of launch in 2013 of the first stiff PVB type no European regulatory or national framework was available to include this material in a structural glass design. Today the option exists to use the properties of this material category either under EN 16612 or with a national standard or approval in most European countries. Stiff interlayers are routinely used for laminated glass thickness reduction. In 2013, costs were the major driver for interest and adoption of stiff interlayers. Going forward, carbon footprint reduction of glass used in facades, and potentially even structural substructures, will become as relevant if not more relevant in interlayer selection. Therefore, interest in design with stiff PVB interlayers is expected to continue to grow.

3. Safety

3.1. Impact

Laminated safety glass is distinguished from laminated glass by its performance under a pendulum impact test and its subsequent classification. In Europe, EN 14449 designates EN 12600 as safety classification standard for CE-marking purposes of laminated glass. Impact performance is rated by dropping a 50 kg impactor (type twin-tire) on a four-side supported test specimen of 1938 * 876 mm from various drop heights. The highest classification is obtained at a drop height of 1200 mm. If the breakage pattern is consistent with that of laminated glass, a 1B1 classification is assigned.

Stiff PVB types can achieve a 1B1 classification already in a 33.2 configuration (two times 3 mm glass with a 0.76 mm stiff PVB interlayer. This is theoretical, as most laminated glass with stiff PVB types is produced using individual glass thicknesses of 5 mm and more (55.2 and thicker). The reason is that typical stiff interlayer applications have limited support (e.g. cantilevered, two-side supported or point-fixed) or concern large glass surface areas. In those cases, low thickness glass cannot be applied. In addition, some of these applications require strengthened glass. If strengthened glass is used, the interlayer thickness is routinely increased to 1.52 mm for quality and durability reasons. This further contributes to impact performance in general.

Interesting enough, French National Approval DTA 6/22-2437_V1 for Saflex Structural indicates that impact tests carried out at 60°C on Saflex™ Structural DG41 XC glazing with composition 44.2 (two clear annealed glasses of 4 mm and a spacer of 0.76 mm) according to the principles of the EN 12600 standard, at a drop height of 1200 mm, presented satisfying results.

Many of the applications in which stiff interlayers are used, require European or national system approvals for the structure as-build on top of a generic EN 12600 classification of the laminated of the glass used. A review of these would be outside of the scope of this article. For balustrades and annealed glass with stiff PVB, a useful overview can be found in Lefevre & Šikyňová, 2019.

3.2. Post-breakage behavior

The post breakage behavior of laminated glass is highly dependent on the glass type used. In contrast to laminated annealed or heat-strengthened glass, the behavior of (fully broken) laminated toughened glass is a strong function of the interlayer properties. Depending on the application of the laminated toughened glass, either just retention of the broken glass in the supports or in addition residual load bearing resistance of the broken laminate can be important. Some examples are available for stiff PVB types for e.g., cantilevered balustrades or point-fixed overhead glazing (Koll et al. 2016). Temperature at which the breakage occurs, and duration of loads if applicable, will be important for post-breakage behavior of broken laminates with stiff PVB interlayers and will need careful evaluation if relevant. In general, use of glass types with larger breaking patterns, such as annealed and heat-strengthened glass, will strongly enhance post breakage performance of laminates.

4. Durability

4.1. Light and solar properties

Standardized tests for durability of laminated glass are described in e.g., EN ISO 12543-4 (stability of light transmission and appearance) and ANSI Z 79.1 (stability of light transmission, color, haze, yellowness index and appearance). Some aspects of durability are a function of the quality of the lamination process as well as the interlayer e.g., the ability to withstand high temperature or humidity. The stability of laminated glass under exposure to natural light or radiation exposure in accelerated ageing experiments is conventionally attributed to the interlayer only. Stiff PVB's types by the major producers can meet the standardized requirements for durability.

The stability of stiff PVB's types under UV radiation has been confirmed by French registration body Cekal and by the CSTB for Saflex Structural in 4000-hour WOM tests to ISO 4892 for light transmission, color and yellowness index.

In addition, French National Approval DTA 6/22-2437_V1 for Saflex Structural indicates that continuous exposure to a temperature of 85 °C for one month does not lead to visible deterioration of the interlayer. The producer of this material indicates that the exposure of the interlayer at 100 °C for one month does not lead to visible deterioration of the interlayer.

4.2. Adhesion

Durability of adhesion is not a property that is routinely directly tested under international standards. However, both French registration and certification body Cekal as well as the CSTB (see section on France) include an adhesion test after a 4000-hour exposure protocol to ISO 4892 (WOM). Cekal uses a black panel temperature of 50 °C and an adhesion torque test on eight to 12 drilled 20 mm diameter samples to determine adhesion. The five highest stress at break values are considered and averaged. The CSTB uses a black panel temperature of 65 °C and adhesion pull test on ten water-jet cut 20 * 20 mm samples to determine adhesion. The stress-at-failure values are compared in Figure 2.

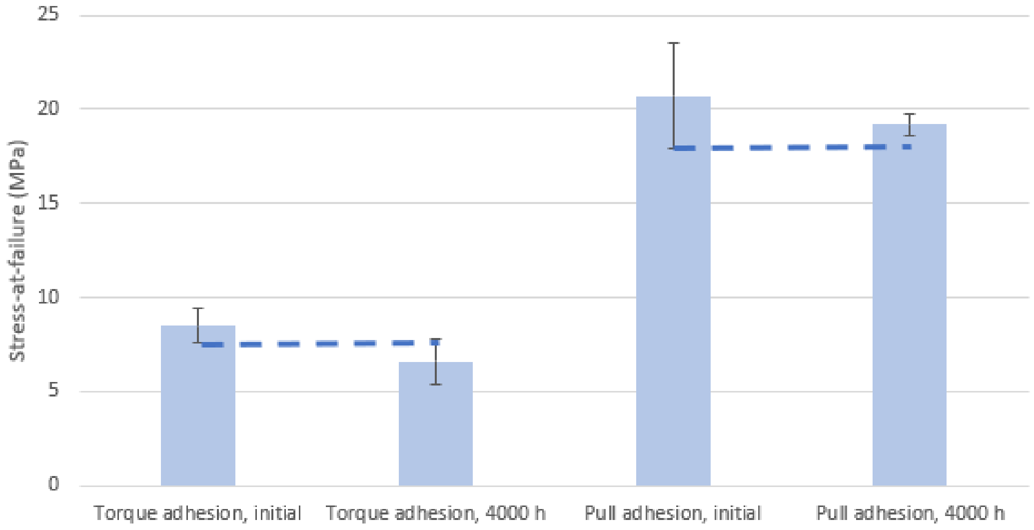

Fig. 2: Stress-at-failure before and after exposure to UV-radiation for 4000 hours in torque and pull adhesion testing.

Both tests indicated no significant drop of adhesion after 4000 hours of UV exposure. It is important to note that in the torque testing, invariably glass failure was noted as failure mode, most likely due to imperfections created in the drilling process. Therefore, the values obtained in torque adhesion testing should be considered as minimum adhesion values. The failure mode for the pull-tests was interfacial glass-interlayer failure and thus provide a more realistic value for adhesion. The latter values are in the same range as determined in compressive shear type adhesion measurements.

4.3. Mechanical properties

Reports on quantification of interlayer modulus properties in laminated glass prior to and after exposure to UV radiation is relatively rare. An example for stiff PVB can be found in Stevels & D'Haene (2021). In summary, three laminated glass specimens were produced on a commercial line for a durability test to EN ISO 12543-4 (UV-radiation) in a 66.2 configuration (360 * 1100 mm) using a 0.76 mm stiff PVB type (Saflex® Structural) as interlayer. These panels - as produced - were subjected to four-point bending experiments in creep mode using a 250 N load at 20, 30 and 50 °C, with deflections monitored for respectively 72, 48 and 24 hours. After characterization of the initial behavior of the panel, the panels were exposed to the conditions of the UV-radiation test. This test has a duration of

2000 hours and requires a radiation intensity of 700 W/m^2 at 45 °C. After exposure for 2000 hours, re-characterization of the panels as above was executed as outlined above. Results were expressed as either deflection or modulus. The latter is shown in Figure 3.

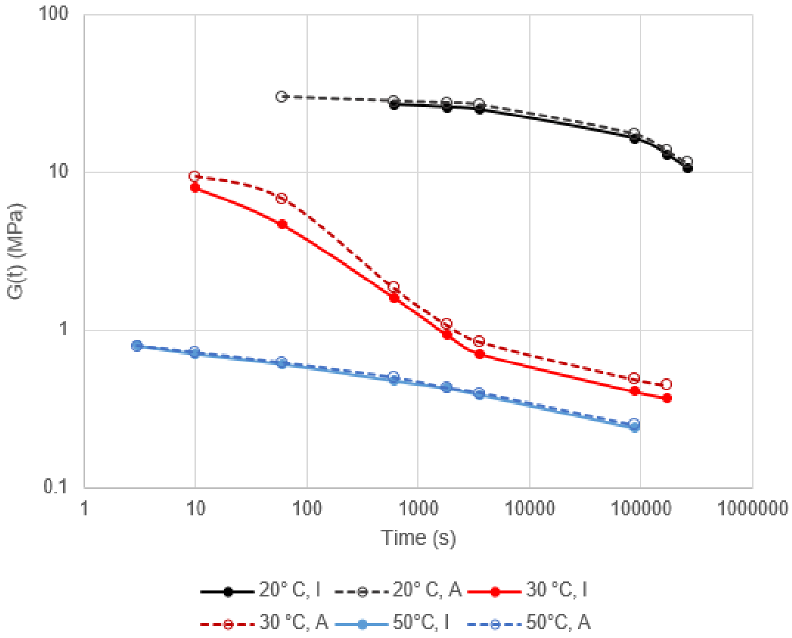

Fig. 3: Modulus values derived from the deflections as measured in Figure 4 on the panels under load prior to exposure (marked I for initial state, solid lines) and after exposure (marked A for aged state, dotted lines) to EN ISO 12543-4.

The mechanical properties of glass laminates did not change upon exposure to UV radiation to EN ISO 12543-4, indicating robustness of the viscoelastic properties of stiff PVB as comprised in laminates. Other experiments, on smaller samples exposed to UV radiation in a WOM test to ISO 4892 and characterized by four-point bending, confirmed these findings (CSTB, 2022).

An indication of stability of interlayer mechanical properties as exposed to temperature can be found in Schimmelpenningh (2019). Glass laminates with an unsupported outer pane of up to 10 mm were stored for 1000 hours at 100 °C. No displacement of the outer pane was observed for a stiff PVB type (Saflex Structural).

4.4. Edge stability

Edge stability of glass laminates can be evaluated using e.g., exposure to demanding (natural) climate conditions, exposure to salt fog in accelerated testing or exposure to other materials commonly used with glazing such as sealants and cleaners. An overview can be found in Schimmelpenningh (2017). A full discussion of the experiments is beyond the scope of this article, but it was found that the edge stability of stiff PVB under challenging conditions was markedly improved as compared to conventional PVB. An example is the development of edge imperfections of exposed edge laminates in the challenging conditions of Florida, USA climate. Edge stability, as defined here, is a long-term event with the samples exposed to the natural outside environment. The edges are unprotected and consequently are wet in the early morning (dew) and during episodes of fog or rain and subjected to high heat and sunlight at other times. The Edge Stability Number (ESN) is a weighted sum of "percent defect lengths" where the weight increases as the square of the depth. The maximum ESN number is 2500 with a minimum number being zero, therefore the smaller the number, the better the edge stability in this environment. Any product exhibiting an ESN of less than 500 is considered exceptional.

Figure 4 shows the difference in ESN between glass laminates utilizing a conventional PVB interlayer and a stiff PVB interlayer, both exposed at the earlier mentioned site for the corresponding duration. Under the conditions of exposure, Saflex DG structural PVB interlayer performance at 40 months is outstanding, with the understanding that an ESN of 500 is considered exceptional.

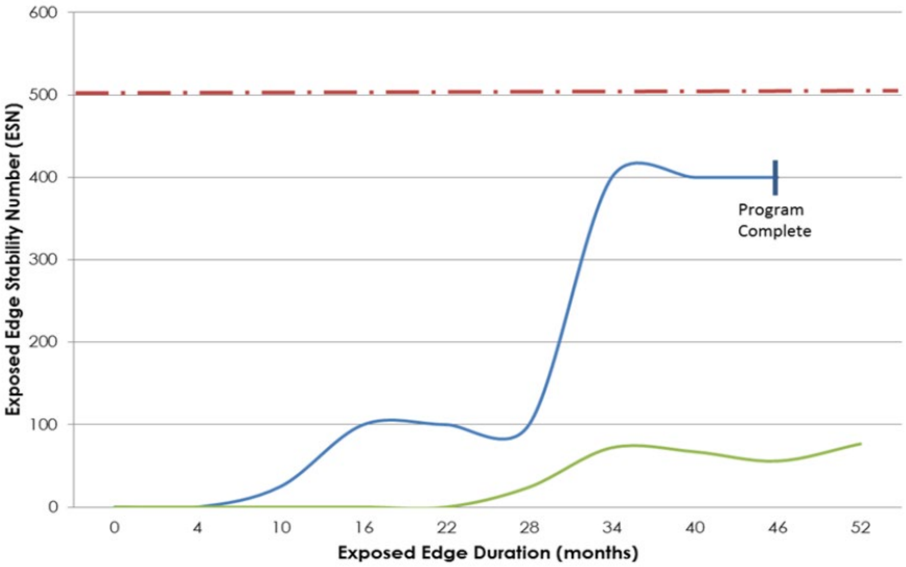

Fig 4: Edge Stability Number development of conventional Saflex® Clear RB (blue line) and Saflex® Structural DG (green line) interlayers of open edge laminates in Florida climate.

Figure 4 serves merely as an illustration of the edge stability differences between the two products. It should not be construed to mean that properly laminated conventional PVB cannot be used in exterior applications, or that structural PVB interlayers are inert to climate exposure in any condition. The results are applicable for the samples as tested and not a guarantee of performance.

5. Mechanical properties for design

During the commercialization and scale-up of stiff PVB's between 2013 and 2020, there were frequent changes in producer modulus data as well as significant differences in properties between producers. Although in hindsight these could largely be attributed to different characterization methodologies or type of modulus reported (e.g Härth et al. 2019), this caused some initial restraint with specifiers in specification of stiff PVB's as they were not sure about which values to use, related to some of the unclarities in EN 16613. Meanwhile, through progress in research in both academia and industry and with the revision of EN 16613 technically complete (although not republished yet) the producer data have started to converge. In addition, the values can be compared to independently established values based on the material models comprised in the German national approvals for stiff PVB. The results for duration between 1 second and 1 month are shown in Figure 5a at 20 °C and in Figure 5b at 35 °C. The latter is a critical temperature as it is just below the dynamic glass transition of stiff PVB types.

At 20 °C, the producer data are in a relatively small band. If 1 MPa is taken as a threshold above which meaningful shear transfer occurs (Kuntsche et al. 2019), it takes at least five days to reach this modulus value. This is mostly relevant for snow loads, and the comparison can be made explicitly for EN 16612 or the German approvals (see there). Interestingly enough, the independently established data for the German approvals are above those reported by the producers, at least for durations over 10 minutes.

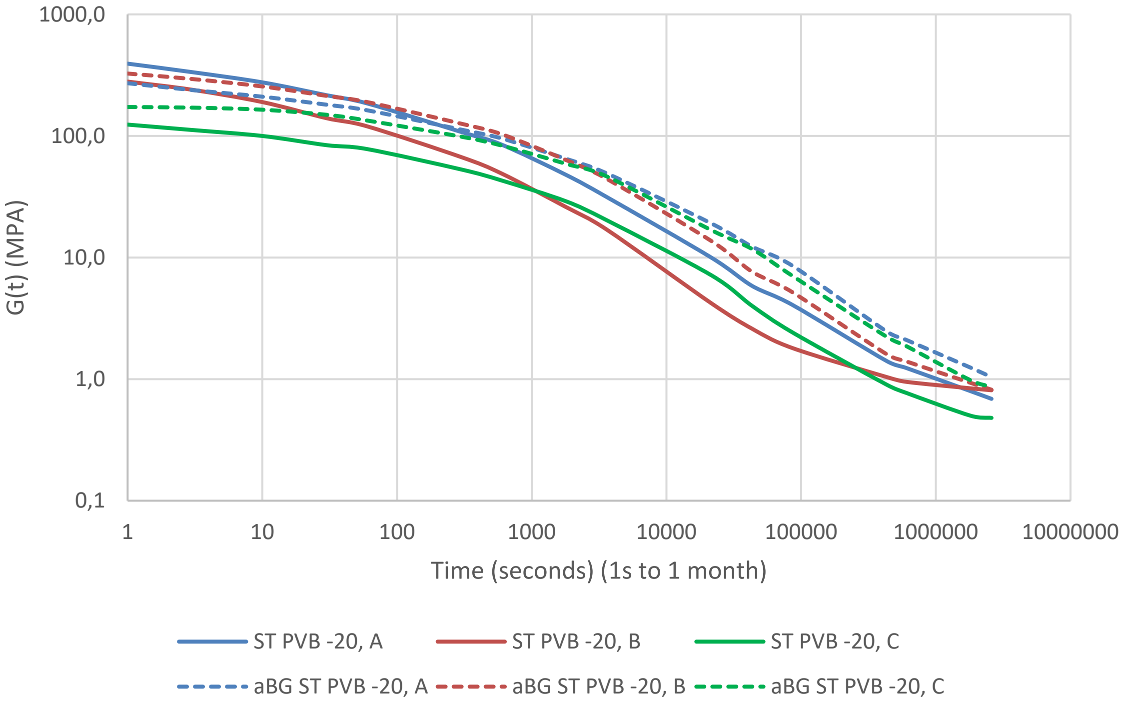

Fig. 5a: Modulus data for stiff PVB at 20 °C based on data from producers A, B and C (solid lines) and the corresponding data as derived from the material models for the same materials in the German National approvals (“aBG”).

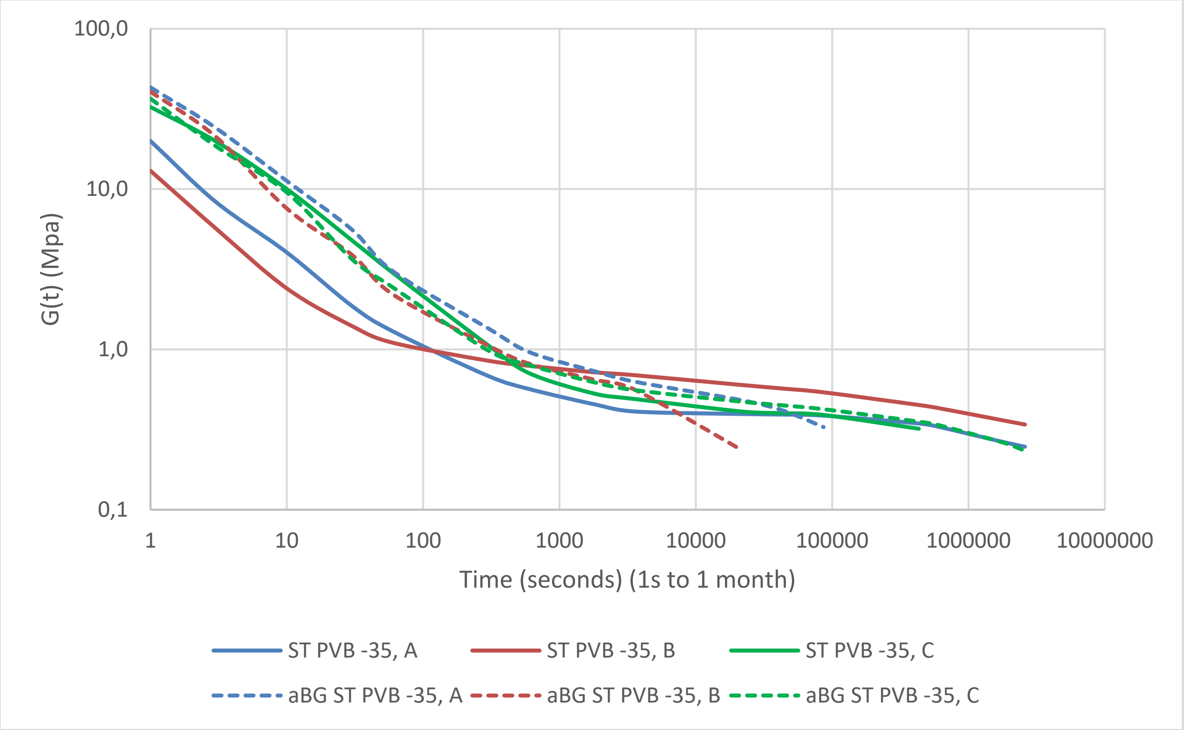

Fig. 5b: Modulus data for stiff PVB at 35 °C based on data from producers A, B and C (solid lines) and the corresponding data as derived from the material models for the same materials in the German National approvals (“aBG”).

It would seem that the producers have erred on the site of caution in reporting their current values. A publication on the determination and verification of interlayer modulus values is available from one of the producers (Stevels & D'Haene, 2020).

At 35 °C, again the curves are in a relatively narrow band, with producers A and B reporting values that are more conservative than in the German approval. This would be relevant in some cases. On average, it takes about 5 minutes for the modulus to drop below the 1 MPa threshold postulated in (Kuntsche et al. 2019). Nevertheless, it is important to review the effect of the modulus in relation to the actual load applied on the relevant glazing configuration, as e.g., glass dimensions, glass and interlayer thickness, and support type play a key role in determining the effect of interlayer stiffness. Projects/case studies/applications

6. Cases/projects/applications

The first large scale application of stiff PVB was for annealed glass balustrades in Belgium and many kilometers of railing with exposed edge have meanwhile been installed. Some better documented project case studies are available in Kothe (2018) and Schieber & Meier (2020), including the iconic spherical shell of the Academy Museum of Motion Pictures Los Angeles by Renzo Piano Building Workshop. Other examples are found e.g. in Berlin (Cube, 3 XN), Brussels (Spectrum, Jasper Eyers) and New York (660 Fifth Avenue 2022 refurbishment, KPF Associates).

7. Conclusions

Today, stiff PVB's can be used for structural glass design within EU, ASTM or National regulatory frameworks. The safety aspects, durability aspects and properties for design are well documented and available from multiple producers The values for design have been independently verified through academic studies and extensive studies in Germany and France in support of national approvals. Ten years after their introduction in the market, reference projects are available and glass designs with slimmer glass and lower carbon footprint are enabled. As the latter is more relevant than ever, continuous use of stiff PVB's in the market can be anticipated for years to come.

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