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Laminated Thin Glass under Torsional Deformation

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Abstract

Thin glass below 2 mm in thickness is becoming increasingly interesting in façades with the growing importance of lightweight construction. Chemically strengthened thin glass offers high strength and flexibility; as a result, its large deflection capacities can be exploited by active cold bending, leading to new applications such as adaptive façades. To meet safety requirements, thin glass should be laminated. However, compared to conventional laminated safety glass, laminated thin glass (LTG) exhibits a much lower glass-to-interlayer ratio. In this study, the behaviour of LTG under torsional deformation was investigated through a long-term experiment. A test rig was developed to evaluate the long-term behaviour experimentally. Specimens composed of two 0.7 mm chemically strengthened thin glass panes with ethylene vinyl acetate (EVA) and multilayer interlayer with EVA and modified polyester (MPE) were subjected to a fixed torsional angle of 30° for 3,100 h (approx. 130 days). The torsional moment was continuously monitored to determine the time-dependent shear stiffness. Afterwards, the fixation was removed to observe the extent of shape recovery. The results showed that even after a recovery time of 800 h (> 30 days), the LTG showed permanent deformation. This highlights the necessity of accounting for the mechanical properties of the interlayer in structural design. This is particularly important for applications involving repeated deformation, such as adaptive façades.

Keywords

Laminated Glass, EVA, Thin Glass, Long-Term, Torsion

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1. Motivation and Objective

In the building industry, glass with a thickness of 2 mm or less is referred to as thin glass. To increase its strength, thin glass is often chemically strengthened, enabling it to achieve higher strength values than thermally prestressed glass. This combination of high strength and low thickness allows the glass to be cold bent beyond conventional limits. This opens up new application possibilities, such as free forms and adaptive façades. Thin glass elements can be shaped through bending, torsion, or a combination of both, thereby increasing their geometric stiffness (Galuppi, 2018; Neugebauer et al., 2018, 2020; Silveira et al., 2018).

Previous research on glass under torsional deformation has primarily focused on glass beams. They are prone to lateral torsional bending due to their slender geometry and loading conditions. Experimental tests were conducted by Belis et al. (2013), Kasper (2005), Kraus (2019), Uheida (2022).

Analytical approaches by Galuppi und Royer-Carfagni (2020) and Kasper (2005) take into account the influence of the shear stiffness of the interlayer on the required torsional moment. In the case of slender beams where the width a is small compared to the length L ($a \ll L$), as considered in this study ($a/L = 0.2$), Galuppi und Royer-Carfagni (2020) have already shown that both calculation methods show a good agreement. Both methods define as a boundary condition that the thickness of the interlayer t is small compared to the thickness of the glass panes h ($t \ll h$). Compared to standard laminated safety glass consisting of

- 2 x 4 mm glass and a 0.76 mm interlayer (glass/interlayer = 10.5) or
- 2 x 4 mm glass and a 0.38 mm interlayer (glass/interlayer = 21.1),

the ratio between glass and interlayer is significantly lower for laminated glass made of thin glass

- 2 x 0.7 mm and 0.76 mm interlayer (glass/interlayer = 1.8) or
- 2 x 0.7 mm and 1.52 mm interlayer (glass/interlayer = 0.9).

In addition, the analytical approximation is only valid for small deformations, for which a linear relationship exists between strain and displacement quantities.

These two boundary conditions no longer apply to thin glass. First $t \approx h$, and, second, larger torsional angles are possible due to the high strength. The specific behavior of thin glass under torsional loading was investigated by Galuppi & Riva (2022). In their paper torsional deformation was used to evaluate the glass strength. Their work showed that the torsional moment and shear stress of thin glass panes at high torsional angles (up to 50° corresponding to a torsional angle per unit length of 0.87 rad/m) cannot be adequately predicted using linear analytical calculations, as numerical simulations yielded significantly higher stress values. For the geometry investigated in their study (1000 × 500 mm), the 2.1 mm thick pane already undergoes torsional buckling at a twist angle of approximately 4°. As a result, the response at larger torsional angles corresponds to a strongly nonlinear post-buckling state (Galuppi & Riva 2022).

However, the torsional behavior of laminated thin glass has not yet been addressed. Laminated glass is essential for ensuring safety requirements in construction applications. Thin glass, when subjected to high bending stresses during cold bending, can fail explosively into small fragments due to the high stored strain energy (Galuppi & Riva, 2024; Peters, 2024). This raises the question of how laminated thin glass behaves under torsional loads and to what extent the interlayer influences the overall response.

This study investigates the behavior of laminated thin glass under torsional deformation. Initially, numerical simulations were performed to explore the influence of torsional angle on the maximum glass stress and torsional moment with the aim of determining a suitable torsion angle for subsequent testing. To gain deeper insights into the long-term durability and time-dependent behavior, a dedicated experimental setup was developed. In this setup, two laminated thin glass specimens were exposed to a fixed torsional angle under controlled conditions, and their long-term mechanical response was systematically evaluated.

2. Materials

2.1. Chemically Strengthened Thin Glass

For the experimental test, 0.7 mm chemically strengthened thin glass was used (Schott Xensation Cover). According to the datasheet (Schott AG, n.d.), the four-point bending strength is 800 MPa. However, the specimen dimensions used were not specified. Since the conventional four-point bending test according to EN 1288-3:2000-06 is not suitable for thin glass due to the large deformations involved (Maniatis et al., 2016), it is therefore likely that smaller specimens were used. This could result in higher measured strength values due to size effects. To obtain comparable and representative strength values, tests should be conducted using a clearly defined test setup, such as the one described in Zaccaria et al. (2022). For a first estimation of the maximum torsional angles, the value from the datasheet is taken as the characteristic strength. The resistance value R_d is calculated according to DIN 18008-1:2020-05 for thermally tempered glass and laminated glass (Equ. (1)). Compared to toughened glass (82.5 MPa), the strength is around six times higher, which allows for higher torsional deformation.

$$R_d = \frac{k_c \cdot f_k}{\gamma_M} \cdot k_{edge} \cdot k_{lam} = \frac{1 \cdot 800\ MPa}{1.6} \cdot 1.0 \cdot 1.1 = 550\ MPa \qquad (1)$$

2.2. Interlayer Material

The interlayer material consists of a combination of ethylene-vinyl acetate (EVA) and modified polyester (MPE). EVA, a copolymer made from ethylene and vinyl acetate, provides flexibility and impact resistance. To improve the rigidity in case of glass failure, a modified polyester (MPE) is incorporated. This MPE film is an amorphous, transparent thermoplastic polymer with a glass transition temperature $T_g > 100$ °and an around 100 times higher Young's modulus compared to EVA (16 N/mm² for EVA vs 1613 N/mm² for MPE) (Fleckenstein et al., 2024). With a Poisson's ratio $\nu = 0.49$ for both materials and and the relationship $G = E/2(1+\nu)$ the shear modulus G_{MPE} .is much greater than G_{EVA}. For the production of the multilayer interlayer, the MPE film is placed between two layers of EVA film and laminated to form a composite. The lamination process is carried out in a vacuum laminator to ensure uniform adhesion and optimal material properties. Due to the much higher shear modulus of MPE, the shear deformation of the laminate is assumed to be governed primarily by the EVA interlayers.

2.3. Laminated Glass under Long-term Loading

The long-term behaviour of laminated glass has been investigated in numerous experimental studies. However, only a limited number of studies have addressed the long-term behavior under torsional loading (Callewaert, 2011; Kasper, 2005; Kraus, 2019). Kasper (2005) investigated laminated glass with PVB interlayer under sustained torsional loading with torsion angles of approximately 0.04 rad/m, a loading duration of 60 h and temperature from 0 °C to 35 °C. The results indicated pronounced viscoelastic effects and showed that some specimens that were tested under 15 °C showed an incomplete recovery after unloading. Kraus (2019) reported full recovery for laminated glass with PVB interlayer and torsional deformations of 0.03 rad/m after loading durations of at least 22 h and for temperatures between 20 °C and 40 °C. These findings highlight the strong influence of both deformation level, time and temperature on the relaxation and recovery behavior under torsional loading. EVA interlayer is commonly assumed to behave linear-viscoelastic for small deformations, as they normally occur in intact laminates (safety) glass (Hána et al., 2019; Schuster et al., 2018). For these cases a complete recovery is therefore generally expected within engineering-relevant time scale.

3. Preliminary Consideration

One main question before starting the experimental investigation was the decision for a torsional angle. Galuppi & Riva (2022) have already shown, analytical calculations underestimate the torsional moment as well as the glass stresses. Therefore, a numerical pre-simulation was conducted using the software ANSYS 2024 R2. A monolithic glass pane with a thickness of 2.16 mm was modelled to simulate the case of full shear coupling, as this leads conservatively to the highest glass stresses. The dimensions are displayed in Figure 2. The glass and clamps (polyetherimide, PEI), see Figure 3, were modeled using 3D elements (SOLID 186). The material properties used are provided in Table 1. All materials were modeled as isotropic elastic. For the meshing an element size of 3 mm and 2 elements in thickness were used. Large deformations were activated.

One clamp was fully fixed with all degrees of freedom constrained (x, y, z = 0, rotation: x, y, z = 0). The clamp on the other side allowed torsional rotation around the x-axis and displacement in x-direction, while all other translations and rotations are constrained (y, z = 0, rotation y, z = 0). The prescribed torsional deformation was applied incrementally on this clamp through predefined rotation steps with an increase of 5° per step. The self-weight of the laminated glass was neglected. The required torsional moment to achieve the specified rotational angle and the maximum principal stress was calculated. The results are shown in Figure 1.

Table 1: Material properties for the numerical model.

	Density g/cm^3	Young's modulus MPa	Poisson's ratio
Glass (Schott AG, n.d.)	2.48	74,000	0.215
Clamps	1.28	3,200 (Ensinger, 2023)	0.4

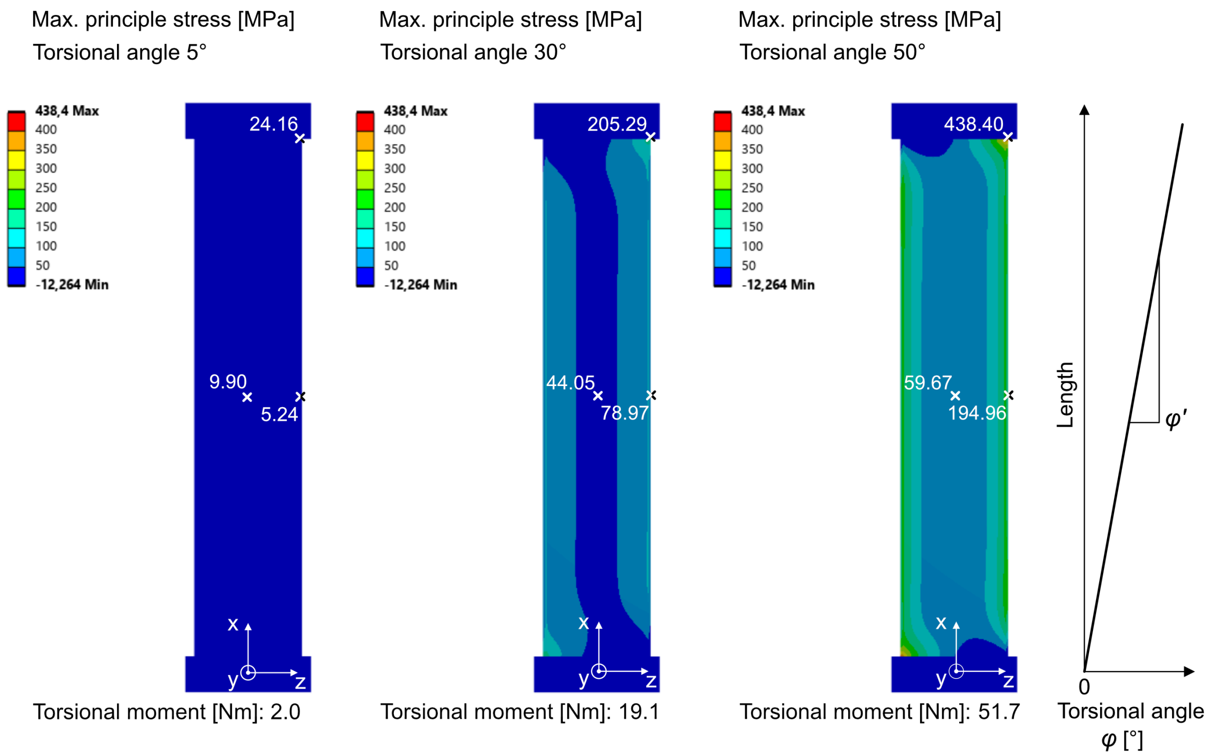


Fig. 1: Torsional moment and maximal principal stresses at large deformations for a monolithic glass with 2.16 mm thickness and different torsional angles.

To be on the safe side, a torsional angle of φ = 30° was chosen, which corresponds to a torsion angle per unit length of φ' = 0.9 rad/m. For this angle, the max. principal stress is less than 50 % of the glass strength.

4. Experimental Investigation of Torsional Deformation

4.1. Specimens

The laminated thin glass panes have a length L = 616 mm and a width a = 120 mm. The short edges of the glass pane are supported in clamps. The clamping length is c = 20 mm on each side, resulting in a span L_s = 576 mm (Figure 2). The laminated glasses are made out of 2 x 0.7 mm chemically strengthened thin glass and two different types of interlayers were investigated. The details of the laminated glasses are shown in Figure 3. One specimen has a 0.76 mm EVA interlayer (EVA) and the second specimen has a multilayer 0.2 mm EVA, 0.2 mm MPE, 0.2 mm EVA (0.6 mm total), referred to as EVA+MPE. Due to the high stiffness of the MPE film, it is assumed that the shear deformation is predominantly accommodated by the EVA layers. Consequently, the shear deformation in the EVA film is expected to be higher in the laminate containing MPE than in the laminate with a pure EVA interlayer.

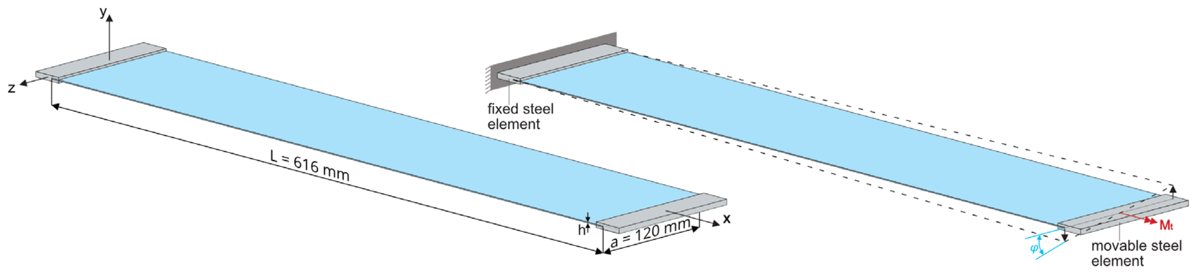


Fig. 2: Geometry and torsional deformation (figure adapted from Galuppi & Riva, 2022 licensed under CC BY 4.0; modifications by the author.).

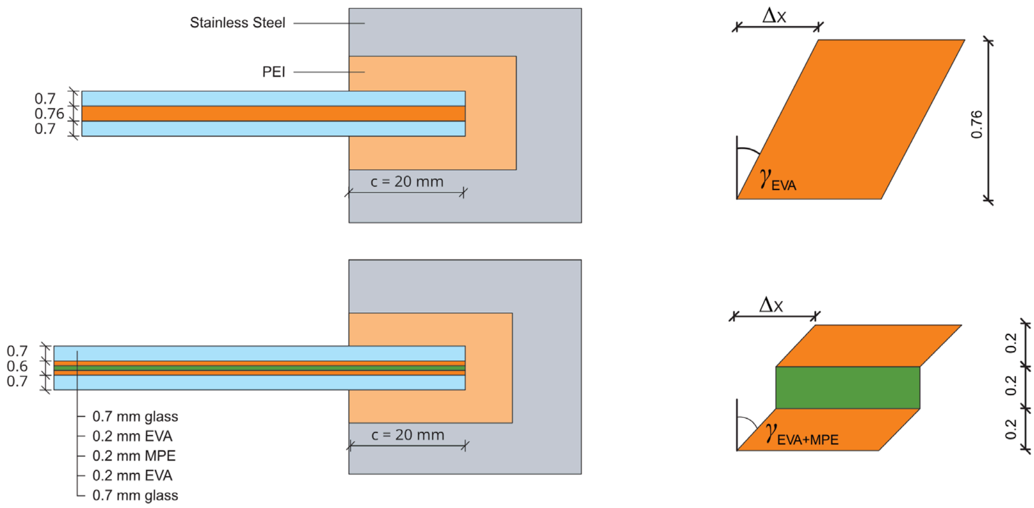


Fig. 1: Left: Detail of clamping area with and laminated glass. Right: Expected shear deformation ($\gamma = \Delta x / \sum t_{EVA}$).

Figure 3 shows the expected shear deformation under pure shear, with the assumption, that $G_{MPE} \gg G_{EVA}$. For the same shear deformation Δx, the shear strain γ_{EVA} is lower than $\gamma_{\text{EVA+MPE}}$, due to the higher total thickness of the EVA in the specimen with pure EVA interlayer. Since for the same shear modulus higher shear strains led to higher shear stresses ($\tau = \gamma \cdot G$). Therefore, higher forces or torsional moments are expected for the EVA+MPE laminate for the same torsional angle.

4.2. Test-Setup

A test setup was developed to systematically investigate the long-term relaxation behavior of laminated thin glass under torsional deformation. The main questions are how the torsional moment and glass stresses change with time and how the MPE interlayer influences these values. Moreover, the recovery after unloading is measured quantitatively.

Figure 4 shows the test setup. The test rig was designed to accommodate two test specimens besides of each other. Both specimens were subjected to a fixed torsional angle of 30°. Both short edges of the glass were inserted into clamps. One clamp was fixed, while the other clamp was free to rotate around the longitudinal axis (x-axis). The fixed clamp was mounted to the frame of the test rig at a 30° angle. At the beginning of the experiment, the rotatable edge was slowly twisted until the clamp reached a horizontal position. In this position, the clamp was secured to the load cell (max. 1.25 kN) using a screw. This ensures that the force was transferred vertically to the load cell. The distance between the rotation bearing and the load cell was 150 mm. Details of the rotational bearing are shown in Figure 4 (bottom).

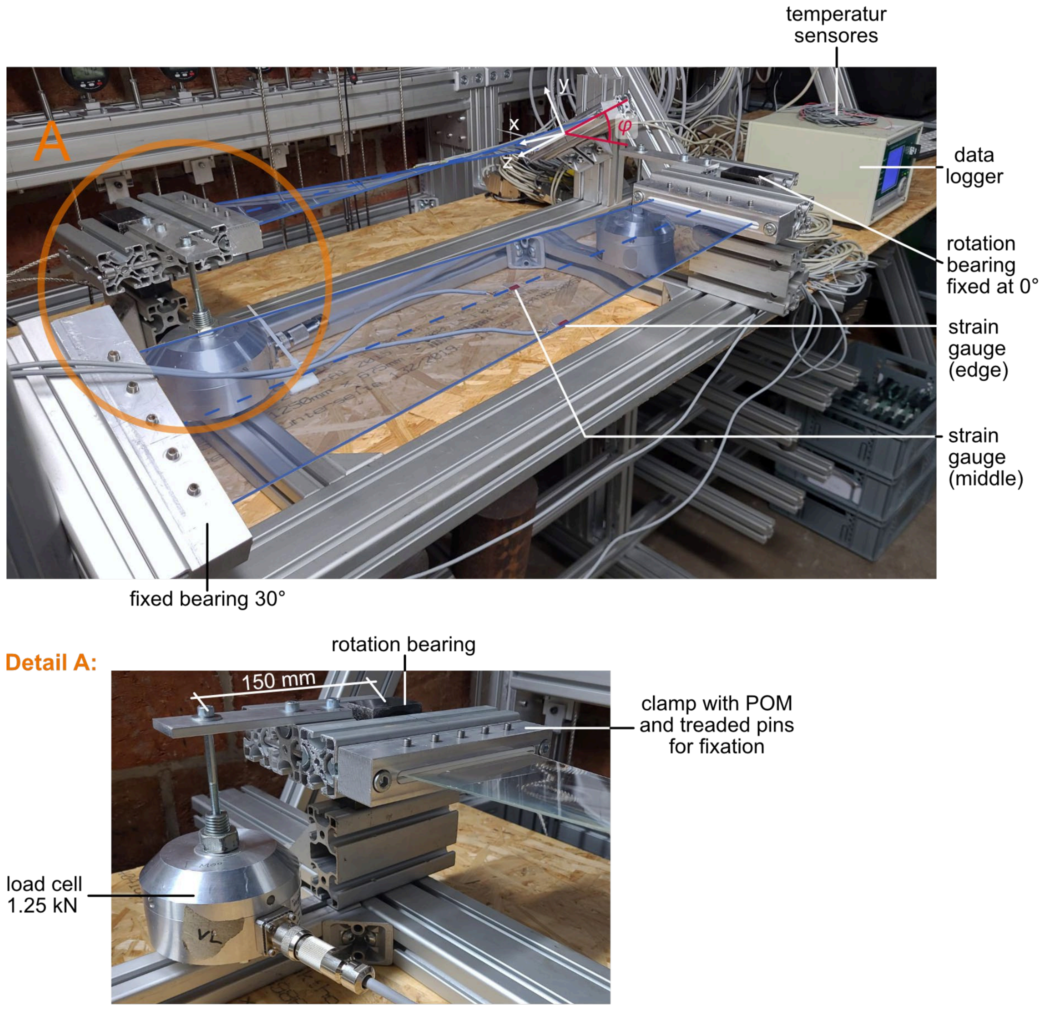


Fig. 2: Top: Test setup. Bottom: detail of clamps to measure relaxation. The glass panes are highlighted in blue to improve visibility.

The laminated thin glass specimens were clamped between two polymer layers (Polyoxymethylene, POM) and secured against slipping with threaded pins. In addition to force measurements using the load cells, strain gauges were adhered to the glass surface to measure the longitudinal strains at the edge and in the center of the pane. Stresses were then derived from the measured strains using Hooke's law and Young's modulus for glass given in Table 1. Strain gauges were positioned at specimen midspan (L_s / 2 = 288 mm) with one strain gauge at the edge and one in the middle of the pane. The strain gauges were zeroed with the specimens unloaded on a flat, level surface. The specimens were then clamped and deformed, so that strains were measured relative to the initial, undeformed state.

The experiment was conducted in a climate-controlled room to ensure consistent environmental conditions with a relative humidity between 50 % and 55 % and a temperature of 23 ± 1 °C. In addition, the room temperature was continuously monitored throughout the experiment. The specimens were left for 3100 hours (~18.5 weeks). Measurements were recorded every 30 seconds for the first 8 hours, then every 10 minutes, and after one week every 30 minutes.

5. Results

5.1. Relaxation

The measured force is used to calculate the torsional moment with the lever arm (150 mm). Due to the expected relaxation of the interlayer, the torsional moment is expected to decrease over time. The same is expected for the stresses derived from the strain gauges measuring signals.

Figure 5 shows the torsional moment (solid lines) and the stresses from the strain gauges (dashed lines) over time in logarithmic scale. The values of both specimens EVA (blue) and EVA+MPE (green) are presented. In addition, the temperature during the examination is added in orange. During this time, the temperature was between 22.7 °C and 23.8 °C. Due to a problem with the climate control unit temperatures and temperature fluctuation increased after 10 weeks. Therefore, for a quantitative analysis only values until week 10 are used. The exact values after 10 seconds and 10 weeks as well as the differences between the start and end values can be found in Table 2.

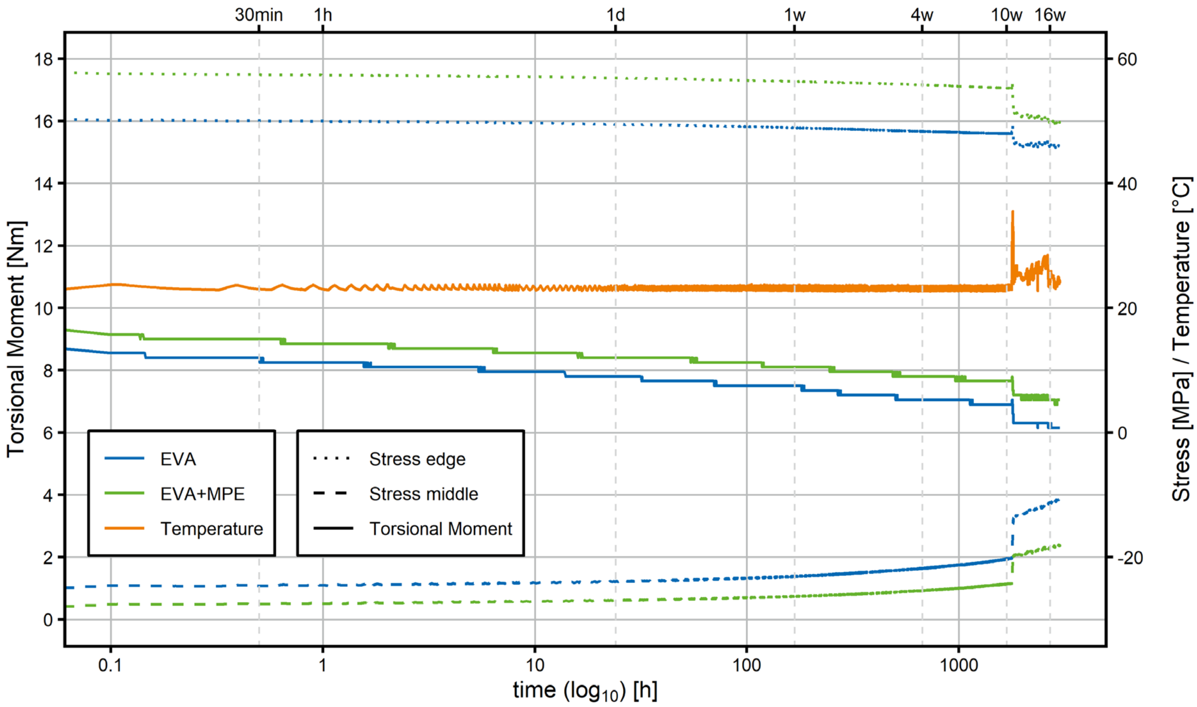


Fig. 3: Torsional moment over time, stress-time diagram showing the strain gauge stresses in the middle and the edge of each specimen and ambient temperature.

At the start of the test the torsional moment for the specimen with the EVA interlayer was 8.7 Nm and for the specimen with the EVA+MPE interlayer it was 9.3 Nm. After 10 weeks, the EVA+MPE specimen showed a 17.8 % decrease in torsional moment, which is 2.9 % lower than the 20.7% decrease observed in the EVA specimen. The strain gauges on the edge of the specimen are loaded in tension, while the middle part is compressed. Both the tensile and compression stresses decrease with time. Both absolute and relative difference are higher for the stress in the middle of the glass pane. The differences between the specimens are small.

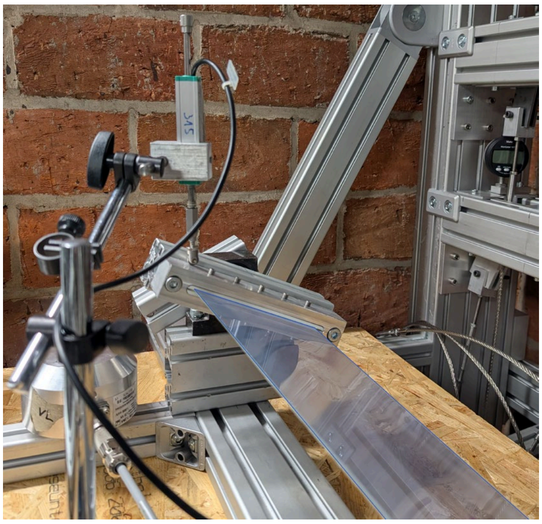
Table 2: Measured torsional moments and stresses after 10 seconds and 10 weeks as well as the decrease in %.

Time	Moment EVA [Nm]	Stress middle EVA [N/mm²]	Stress edge EVA [N/mm²]	Moment EVA+MPE [Nm]	Stress middle EVA+MPE [N/mm²]	Stress edge EVA+MPE [N/mm²]
10 sec	8.7	-24.9	50.3	9.3	-27.9	57.8
10 weeks (1680 h)	6.9	-20.4	48.0	7.7	-24.3	55.3
Absolute difference	1.8	4.5	2.2	1.7	3.6	2.5
Relative difference [%]	20.7	18.1	4.4	17.8	12.8	4.3

This finding aligns with the expectation, that the EVA+MPE specimens need a higher torsional moment for the same torsional angle, due to higher shear strains in the EVA interlayer. However, the difference is small and cannot be considered statistically significant, since only one specimen per interlayer was tested. The elevated temperature resulted in a significant reduction in stresses and torsional moment, reflecting the temperature-dependent behavior of the interlayer, which leads to a reduced shear modulus at higher temperatures. The relaxation behavior returned to a stable trend once the temperature was controlled.

5.2. Time-dependent recovery

For the evaluation of the time-dependent recovery, the specimens were detached from the load cell, and allowed to rotate freely in torsion. The vertical part of the deformation was measured with a displacement transducer (GEFRAN PY) (Figure 6, left). The transducer output was recorded at 0° and 30° as reference values. For all other deformation measurements, the torsional angle was calculated using trigonometric relationships. After the repair of the climate-control-system, controlled temperature conditions were restored prior to unloading. Recovery measurements were performed under these conditions.



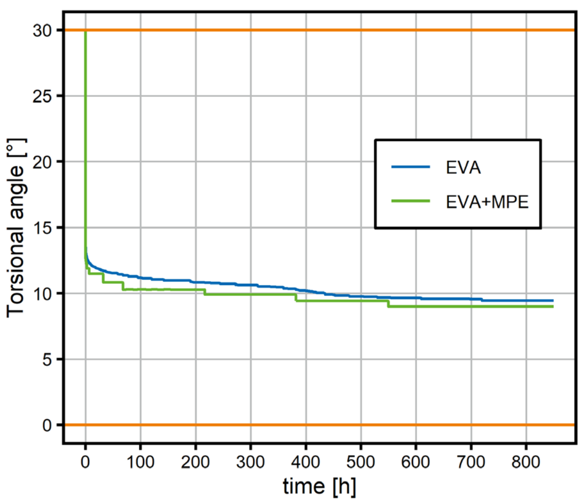


Fig. 4: Left: Specimen with displacement transducer after 850 hours of recovery.
Right: Time-dependent recovery. Torsional angle over time.

Figure 6 right shows the development of the torsional angle over 850 hours (approximately 35 days) for both specimens, EVA (blue) and EVA+MPE (green). The orange horizontal line at 30° represents the start value of the torsion. A deformation of 0° means, that the pane is fully recovered. Both materials exhibit a rapid decrease in torsional angle during the initial phase, followed by a gradual stabilization until the curves reach a plateau. Both materials stabilize at remaining torsional angles around 9°, with the EVA+MPE value being slightly lower with 9.0° compared to 9.3° for EVA. The step-like decline in the green curve is likely due to the displacement measurement setup. Because the transducer measures in vertical direction, the measuring axis is not perpendicular to the clamp surface. In addition, the contact angle changes during recovery. To ensure a continuous contact a wheel was added to the tip of the displacement transducer (Figure 6, left). The steps-like pattern may result from non-uniform wheel motion caused by a slight misalignment or an increased friction, and the wheel therefore rather moved in stick–slip motion at times. It is recommended to use a more direct way to measure the torsional angle e.g., with a rotation angle sensor. EVA and EVA+MPE show comparable recovery after long-term deformation. This means that after more than 30 days, the specimens still show a significant residual deformation. However, it should be mentioned that the displacement transducer and gravity act as a counterforce opposing the reverse deformation. According to the displacement transducers datasheet (GEFRAN spa, 2023) the displacement force is ≤ 4 N which results in a torsional moment of up to 0.25 Nm (between 2.7 % and 3.6 % of the torsional moment from the relaxation test).

Figure 7 shows the specimens after disassembly. Both specimens showed no signs of optical aging or delamination but still show visible deformation.

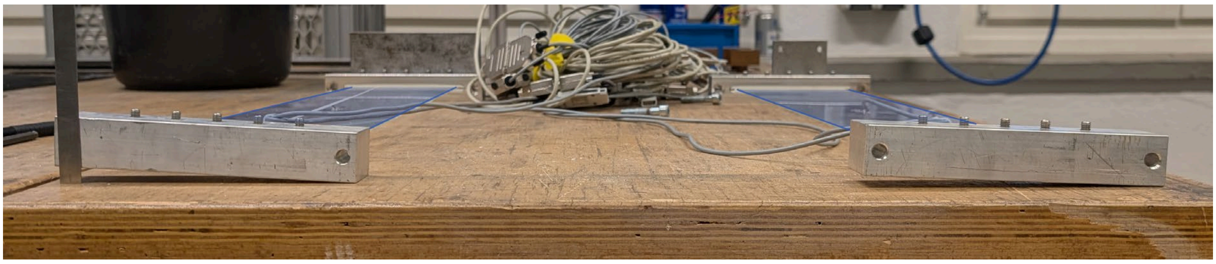


Fig. 5: Specimens after disassembly. Even when lying flat, they still show a visible deformation.

6. Discussion

The long-term experiments revealed that the laminated glass specimens did not fully recover their deformation after unloading. As glass exhibits linear elastic behaviour, the observed residual deformation cannot originate from the glass plies and must therefore be attributed to the interlayer material. For these cases a complete recovery was expected within engineering-relevant time scale. However, in the present study, incomplete recovery was observed within a recovery period of 850 h.

This behaviour indicates that the viscoelastic response of the interlayer may deviate from linearity under the investigated torsional angle. One possible explanation is related to the reduced thickness of the glass plies, which leads to a lower torsional stiffness of the laminated glass and, consequently, to reduced restoring stresses acting on the interlayer. As a result, the driving force for recovery may be insufficient to fully reverse the accumulated time-dependent deformation. Alternatively, the interlayer may have been subjected to strain levels exceeding the linear viscoelastic range. The elevated strain levels are a result of the higher strength of the chemically strengthened thin glass plies, which allow for greater deformation. Both effects may therefore contribute to the residual deformation observed in the experiments, suggesting a nonlinear viscoelastic response of the interlayer within the investigated deformation and time scale.

From an engineering perspective, this finding is of particular relevance for adaptive façade applications, where a fast (within a few minutes) and reliable recovery of deformation is required to maintain functionality. If the interlayer material does not provide sufficient recovery within the required time frame, additional restoring measures or external forces may be necessary to enable the desired reconfiguration of laminated glass elements.

7. Summary and Outlook

With the growing importance of lightweight construction in façades, thin glass (≤ 2 mm) is becoming increasingly interesting. Chemically strengthened thin glass offers high strength and allows for designs utelize its large deformation capacities by cold bending. To ensure safety, thin glass can be laminated. Cold bending increases structural stiffness, but exposes interlayers to long-term shear strains. The study examined ethylene-vinyl acetate (EVA) and a multilayer interlayer including EVA and modified polyester (MPE). The main reason to add MPE is to increase post-breakage rigidity. However, it is not known how these material behaves under long-term deformation and large strains.

One specimen with an EVA interlayer and one specimen with a multilayer EVA+MPE were subjected to a fixed torsional angle over 3100 h. The time-dependent recovery was investigated after unloading. Both EVA and EVA+MPE specimens exhibited comparable relaxation. For the EVA specimen, the torsional moment decreased by 20.7 %, while for the EVA+MPE interlayer it decreased from by 17.8 %. Both specimens showed incomplete recovery, stabilizing at a residual angle of approximately 9°. The EVA+MPE interlayer exhibited slightly higher initial torsional stiffness and reduced relaxation compared to EVA alone. However, the differences are small. Since only one specimen per interlayer was tested, further tests should be carried out for verification. However, the uncomplete recovery has to be taken into account especially when planning movable, adaptive façade elements.

Future research should focus on the influence of different torsional angles and temperatures on relaxation and recovery. The unplanned rise in temperature at the end of the experiment already highlighted its importance. In this context, numerical investigations of laminated thin glass should be conducted in order to determine the stress distribution over the laminate area with a focus on the strain in the multilayered interlayer. This will enable conclusions regarding the shear modulus of the interlayer. Moreover, the performance of laminated glass under cyclic deformation and other bending modes should be investigated. This will contribute to the development of safer and more efficient lightweight façade systems.

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