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Dynamic testing of All-Glass Balustrade

Abstract

Transparency is considered a defining feature of contemporary architecture, both in social housing and single-family homes. Glass balustrades are gaining increasing importance as they combine functionality, safety, and aesthetic lightness. Particularly popular are all-glass balustrades with linear support along the bottom edge (base shoe or clamping system) or point-fixed support (glass clamps), which do not require visible steel posts or frame profiles and therefore contribute to a clean and minimalist architectural appearance. Despite their filigree appearance, these constructions must meet high safety and structural performance requirements. With the ongoing development of relevant standards and guidelines, especially the forthcoming EUROCODE for structural glass design, requirements for impact resistance, fall protection, and the prevention of hazards caused by falling glass fragments are being increasingly specified. The aim is to ensure the safe and code-compliant use of glass elements in architecture. This paper focuses on the dynamic verification of fall protection for bottom-clamped all-glass balustrades and compares different verification methods based on pendulum impact testing, including test certificates provided by system manufacturers, experimental investigations, and numerical simulations. The advantages and disadvantages of the respective assessment methods, as well as existing normative gaps and uncertainties, are discussed.

Keywords

All-Glass Balustrade, Pendulum Impact Test, normative Gaps, numerical Simulation, Modelling of Structure,

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1. Introduction

In contemporary architecture, transparency plays a central design role, both in multi-storey residential buildings and in private single-family homes. Against this background, glass balustrades are becoming increasingly widespread, as they meet safety requirements while enabling a light and unobtrusive appearance. All-glass balustrades with either continuous linear support or point-fixed support by means of glass fixings at the bottom edge are of particular importance, as they can be constructed without visible posts or frame profiles, thereby supporting a reduced and minimalist architectural concept for façades and interior spaces. Despite their seemingly delicate construction, these components must be designed and dimensioned to reliably satisfy demanding safety-related and structural requirements. Figure 1 shows an example for a linear supports all-glass balustrade.

Fig. 1: All glass balustrade (Julius Fritsche GmbH).

In principle, three approaches are available to verify load-bearing capacity and serviceability: the use of regulated systems with test certificates or general building authority approvals, experimental verification, and numerical simulations. In practice, however, test certificates are often not directly transferable to the specific installation situation, making a project-specific verification on a case-by-case basis necessary. In some cases, verification by means of the more cost-effective numerical simulation could not be achieved and had to be demonstrated instead by more elaborate and costly experimental tests. It may occur that the required verification cannot be demonstrated by means of numerical simulation, while the same behavior can be successfully verified through experimental investigations. This circumstance prompted a more detailed investigation of this issue.

2. General Arrangement of All Glass Balustrades

The following, the discussion focuses to linearly supported glass balustrades. A typical frameless glass balustrade, as illustrated in Figure 2a, consists of a base shoe forming a continuous clamping profile in which the glass panel is securely held along its bottom edge; an optional edge protection or cap rail may be provided along the top edge to protect the glass and improve user safety. To satisfy fall-protection requirements and applicable building standards, the glazing must be specified as laminated safety glass. Depending on the architectural design and floor buildup, the glass may, for example, be installed flush with the finished floor level or elevated on a plinth, as shown in Figure 2b, allowing integration with different waterproofing or paving configurations.

The base shoe can, for example, be attached laterally to the side of a supporting steel section or mounted from above onto a steel profile by means of bolted connections, as depicted in Figures 2c and 2d. Alternatively, the clamping profile may be fixed directly to a reinforced-concrete substructure using anchor bolts, thereby providing a reliable load transfer into the primary structure. This configuration is illustrated in Figure 2e.

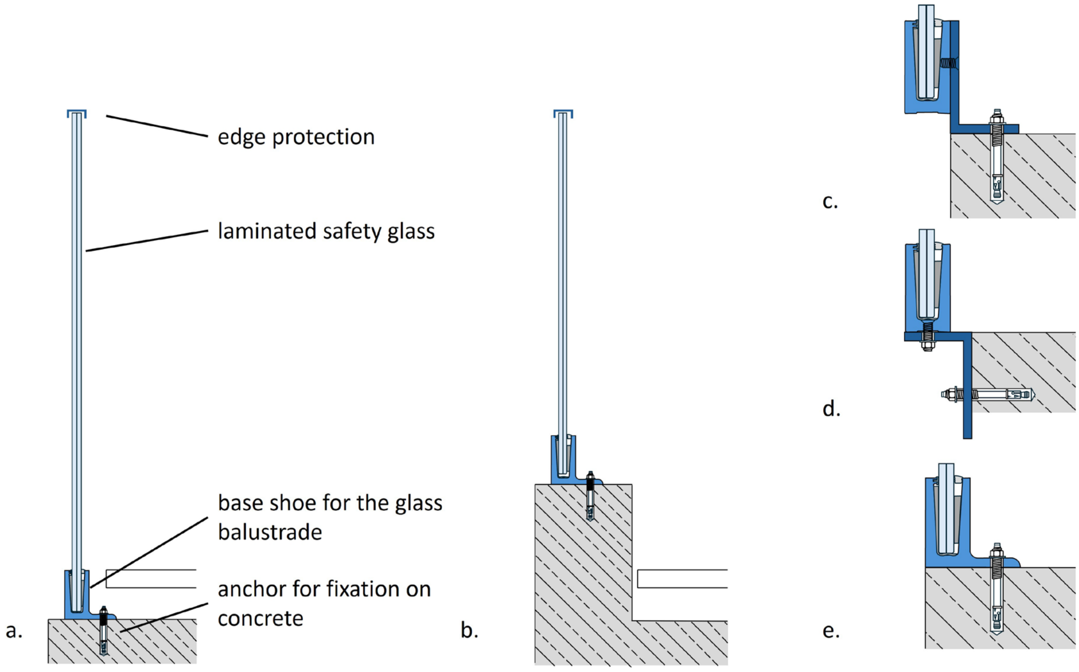

Fig. 2: General arrangement of all glass balustrade.

3. Standards and Guidelines

Regarding the requirements for all-glass balustrades, the existing standards DIN 18008-4 and ÖNORM B 3716-3 are compared with the future Eurocode EN 19100-1 (prEN 19100-1, 2023).

3.1. Comparison of Standards

According to DIN 18008-4, the present glazing without a load carrying handrail, as shown in Figure 2a. is classified in category B and must comply with the corresponding requirements, in particular with regard to the permissible glass build-up and edge protection. For experimental verification, a pendulum drop height of h_F = 700 mm is to be applied. In the numerical verification, a basic impact energy of E_{Basis} = 100 Nm must be assumed, which corresponds to an equivalent drop height of h_F = 204 mm.

According to ÖNORM B 3716-3, the present glazing without a load carrying handrail is classified in glazing group 1.2 and must comply with its requirements, particularly with regard to the permissible glass constructions. A major difference between the two standards – DIN18008-4 und ÖNORM B 3716-3 - is already evident in the permitted glass build-ups: while laminated safety glass made of fully tempered glass is allowed under DIN, this configuration is not permitted in Austria. Another difference concerns the drop height to be applied for experimental verification in residential use: in Germany, a drop height of h_F = 700 mm is required, whereas in Austria h_F = 450 mm is specified. For numerical verification according to ÖNORM B 3716, the same drop height as specified for the experimental verification shall be used.

In the forthcoming EUROCODE 10 - EN 19100-1 and its upcoming corresponding National Annex Document (NAD), the glazing may be assigned to a consequence class (e.g. CC1 or CC2). In addition to the consequence class, glazing must also be classified within a design concept (e.g. LLS-1).

Based on this classification, the design resistance for numerical verification can be determined. The EUROCODE generally delegates the specification of detailed requirements to the respective national standardization bodies.

3.2. Possibilities of Verification

To demonstrate compliance with the fall-protection requirements for such bottom-clamped glass balustrades, three alternative verification methods are available.

- **Test certification**

  The A test certificate is an official document issued by an accredited testing institute that records the results of experimental investigations on a construction product or construction method. It verifies compliance with specified technical requirements under defined testing conditions and provides a basis for evaluating the fitness for use of the tested system.

- **Experimental testing with Pendulum impact test**

  The pendulum impact test is used as an experimental method to verify the impact resistance and post-breakage load-bearing capacity of glass balustrades subjected to human-body-type impact loading. For this purpose, a standardized impactor of defined mass, in accordance with EN 12600 (EN 12600 2003), is released as a pendulum from a specified drop height onto the glazing within the governing impact zone – see in Figure 5a, thereby introducing a reproducible impact energy. The balustrade system is installed in its representative construction configuration, including the clamping profile and fixing elements, and supported in accordance with the relevant normative boundary conditions. Following the impact, the fracture pattern, resistance to fall-through, and the residual load-bearing behavior of the laminated safety glass are assessed. Verification is considered successful if no fall-through occurs and the system continues to provide adequate fall protection even in the fractured state.

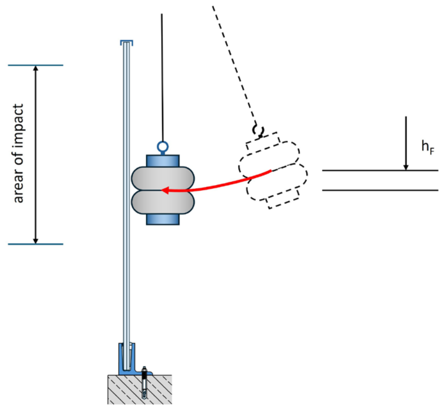

Fig. 3: Pendulum impact test.

- **Numerical simulation**

  Numerical simulation represents a computational verification method in which the load bearing and failure behaviour of the frameless glass balustrade system is modelled under relevant loads and boundary conditions using transient finite element analyses.

  This approach enables a realistic simulation and assessment of time-dependent effects, material behaviour, and the fracture and post-breakage response of the glazing and its supporting system.

4. Short-term Strength of Glass

The following analysis presents a comparison of the short-term strength values used for numerical simulations in accordance with DIN 18008-4, ÖNORM B 3716-3, and the forthcoming EUROCODE EN 19000-1.

4.1. DIN 18008-4

DIN 18008-4 uses the 5 % quantile value as the basis for determining short-term strength. This strength is then used to calculate the short-term design strength with the k_{mod} factor according to Equation (1).

$$f_{Rd} = \frac{k_{mod} \cdot f_k}{\gamma_M} \tag{1}$$

Where f_{Rd} is the designed bending strength, k_{mod} is modification factor and γ_M is material partial factor.

4.2. ÖNORM 3716-3

In ÖNORM 3716-3, the short-term strength values are specified as shown in Table 1.

4.3. EUROCODE 19100-1

In Eurocode, the short-term strength for consequence class CC2 can be calculated using Equation (2).

$$f_{g,d} = \lambda_A \cdot \lambda_l \cdot k_e \cdot k_{mod} \cdot \frac{k_{sp} \cdot f_{g,k}}{\gamma_M} + k_p \cdot k_{e,p} \cdot \frac{f_{b,k} - f_{g,k}}{k_i \cdot \gamma_p} \tag{2}$$

Where $f_{g,d}$ is design bending strength for accidental design situation, $f_{g,k}$ is characteristic bending strength of annealed glass, $f_{b,k}$ is characteristic value of glass strength after a strengthening treatment, γ_M is material partial factor, γ_p is partial factor for pre-stress on the surface, λ_A and λ_l are coefficients for the size effect, k_e is edge or hole finishing factor, k_{sp} is surface profile factor, k_{mod} is modification factor, k_p is pre-stressing process factor, $k_{e,p}$ is edge or hole pre-stressing factor, k_i is interference factor, accounting for the beneficial statistical interference between the distributions of pristine glass strengths and surface pre-stress.

Table 1: Comparison of short-term strengths DIN - ÖNORM - EUROCODE.

Glass quality	DIN 18008-4	ÖNORM B3716-3	EUROCODE prEN 19100-1
Annealed glass	81 MPa	80 MPa	49 MPa
Heat strengthened glass	119 MPa	120 MPa	80 MPa
Fully toughened glass	168 MPa	170 MPa	142 MPa

4.4. Strength of glass in experimental testing

The strength of glass in experimental testing exhibits statistical scatter due to the random distribution of surface and edge flaws, which is typically described by Weibull distribution.

For heat-strengthened glass (HS glass), the literature reports Weibull parameters in the range of approximately m = 7 to m = 10.

Lower values are characteristic of edge-dominated fracture mechanisms and component-like boundary conditions, whereas higher values are observed for surface-controlled failure modes (Schneider & Wörner, 2016).

Figure 4 shows the Weibull distribution for heat-strengthened glass (HS glass) with a Weibull modulus of $m = 8$. The 5% quantile of the strength is taken as 70 MPa, corresponding to a failure probability of 5% with a confidence probability of 95%. Based on this value, the 95% quantile of the strength is approximately 116 MPa. While at the 5% quantile 95% of the strength values exceed 70 MPa, as illustrated by the blue area in Figure 4, at the 95% quantile correspondingly 95% of the values lie below 116 MPa.

Considering the modification factor k_{mod} = 1.7 specified in DIN 18008-4 for HS glass under short-term loading, the resulting short-term strengths are approximately 119 MPa (5% quantile) and 197 MPa (95% quantile), respectively.

The numerical verification shall generally be performed on basis of the 5% quantile of the short-term strength. In contrast, in experimental verification the actual strength of the tested specimens may lie in the range of higher quantiles, for example close to the 95% quantile. Since glass strength exhibits statistical scatter due to manufacturing-related surface and edge flaws, a successful experimental verification carried out with specimens of high short-term strength (e.g. near 197 MPa) merely demonstrates that these specific specimens possessed a correspondingly high strength. Such a test outcome, however, does not permit a general conclusion for the population, as approximately 95% of glass strengths lie below this level and verification with specimens may therefore also fail.

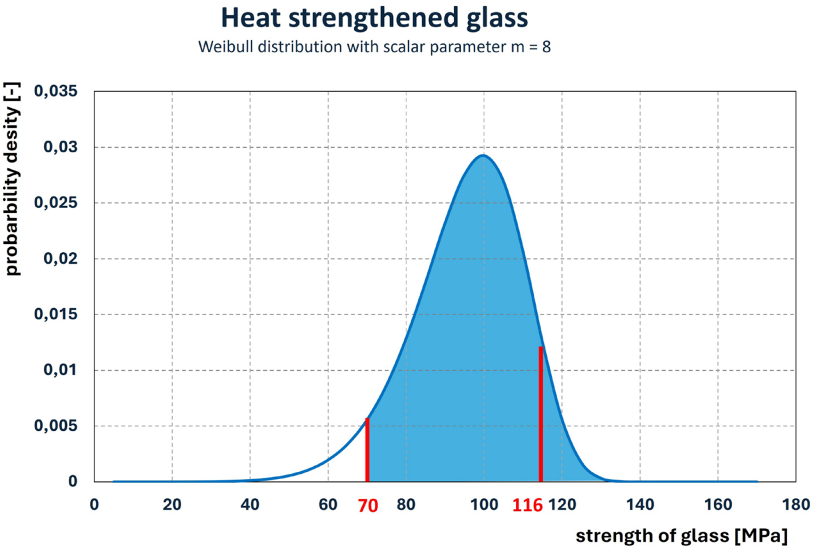

Fig. 4: Weibull distribution of strength of glass.

5. Area of Impact

DIN 18008-4 and ÖNORM B 3716-4 specify minimum distances from free glass edges and from adjacent supports or structural elements, such as posts, rails, handrails, or the finished floor level. The area defined by these edge distances constitutes the impact zone.

Within this zone, verification shall be performed at the most unfavourable location. Accordingly, the experimental or numerical verification may be carried out at different positions, as schematically indicated by points 1 to 3 in Figure 5a.

For balustrade glazing without a load-bearing handrail—whether provided with an edge protection profile or not—the impact zone should be extended to within 100 mm of the top glass edge, as shown in Figure 5b. This is because realistic scenarios may occur, as illustrated in Figure 5c, in which a person is prevented from falling with the main body mass acting at the level of the upper glass edge. Such a pendulum impact (experimental or numerical) can lead to higher stresses than impacts occurring further within the pane.

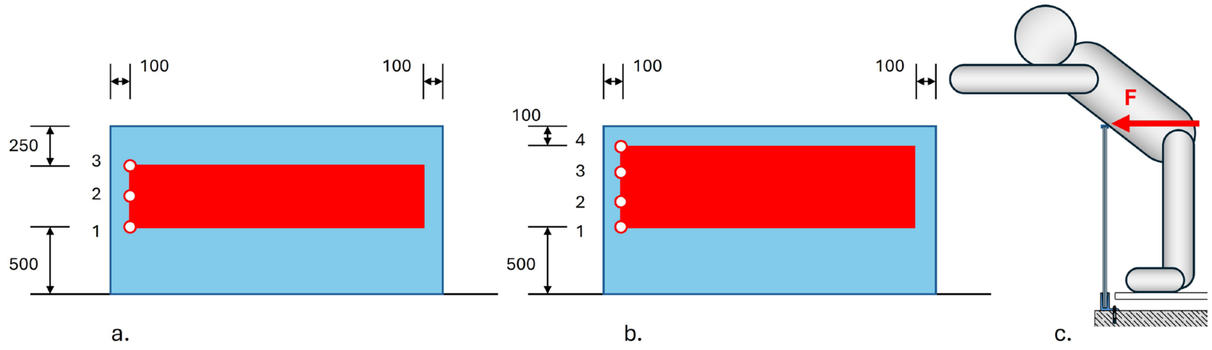

Fig. 5: Area of impact.

6. Modelling of System for numerical Simulation

The greatest challenge in the numerical simulation lies in the realistic modelling of the overall system. The problem can be represented as a mass–spring–mass system, as shown in Figure 6a, subjected to short-term loading. The mass m_1 represents the pendulum mass (50 kg), while the mass m_2 corresponds to the mass of the laminated safety glass pane. Spring C_1 describes the compliance of the twin wheel at the prescribed internal pressure.

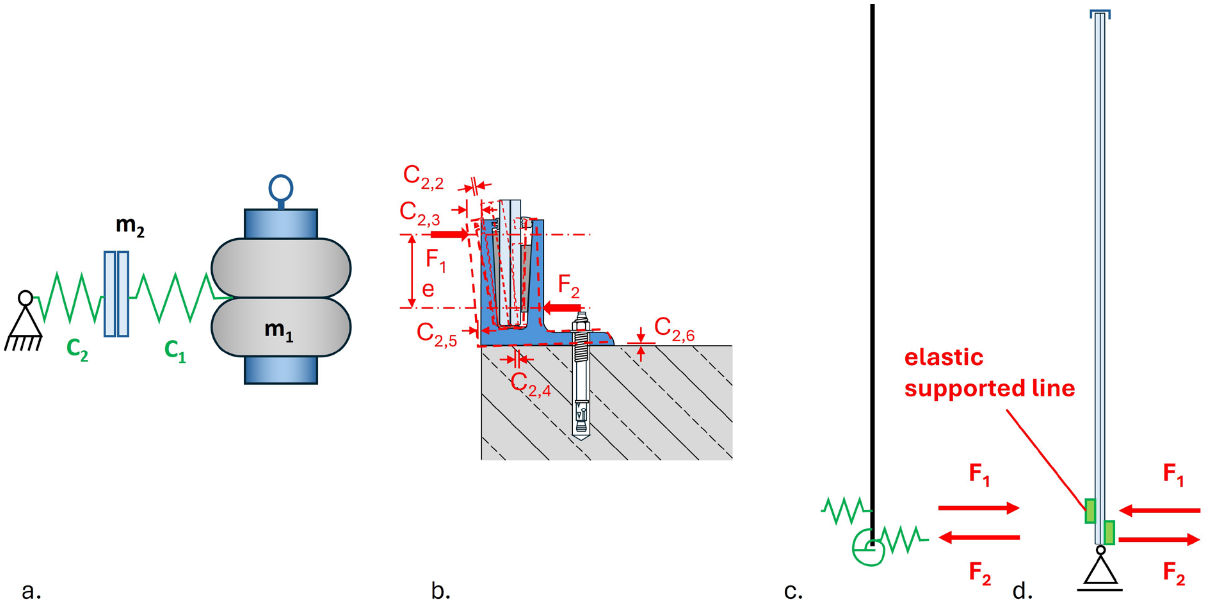

Fig. 6: Mechanical Model – Mass-Spring-Mass-System.

The system stiffness C_2 is composed of several sub-springs that represent the deformation contributions of the support and clamping configuration, as illustrated in Figure 6b:

- $C_{2,1}$ represents the bending stiffness of the glass pane,
- $C_{2,2}$ the stiffness of the polymer interlayer between glass and the metallic clamping profile,
- $C_{2,3}$ the bending and torsional stiffness of the clamping profile,
- $C_{2,4}$ the compliance of the polymer support at the glass edge,
- $C_{2,5}$ the clearance between the fastener and the hole in the metal profile, and
- $C_{2,6}$ possible slip of the anchor within the drilled hole.

These sub-springs allow relative displacements and rotations of the glass pane within the system. Increased compliance of the support conditions results in a reduced impact force during the pendulum test and, consequently, in lower stress levels within the glass. A key difficulty in the modelling arises, on the one hand, from the lack of reliable material parameters, particularly for the polymers used, and on the other hand from the fact that some springs (notably $C_{2,4}$ to $C_{2,6}$) represent stochastic or installation-dependent deformation components that can only be captured deterministically to a limited extent.

The system of translational and rotational springs shown in Figure 5c can be represented in suitable finite element programs by two continuous elastic line supports, as illustrated in Figure 5d. These two elastic lines transfer the forces F_1 and F_2 resulting from the pendulum impact into the substructure and reproduce the displacement and rotational behavior of the real support conditions in the numerical model.

6.1. Materials

In this system of the “all glass balustrade”, many different materials, together with their geometry and material properties, must be represented in the numerical model. Such as glass (E = 70,000 MPa), aluminum (E = 70,000 MPa) or stainless steel (E = 200,000 MPa), POM – polyoxymethylene (E = 2500 – 3500 MPa), or EPDM – ethylene-propylene-diene monomer (E = 5 – 15 MPa). The combination of a wide variety of materials and the specific geometries used by some system manufacturers makes modeling in a finite element program very complex and is therefore not suitable for everyday use in numerical verification.

6.2. Contact issue of Modelling

A particular aspect concerns the modeling of the twin wheel during impact on the glass surface. As shown in Figure 7, the size of the contact area depends on the applied pendulum force. This dependency requires an explicit consideration of the contact problem within the numerical model. The model must be capable of automatically and consistently determining the contact area as a function of the applied load.

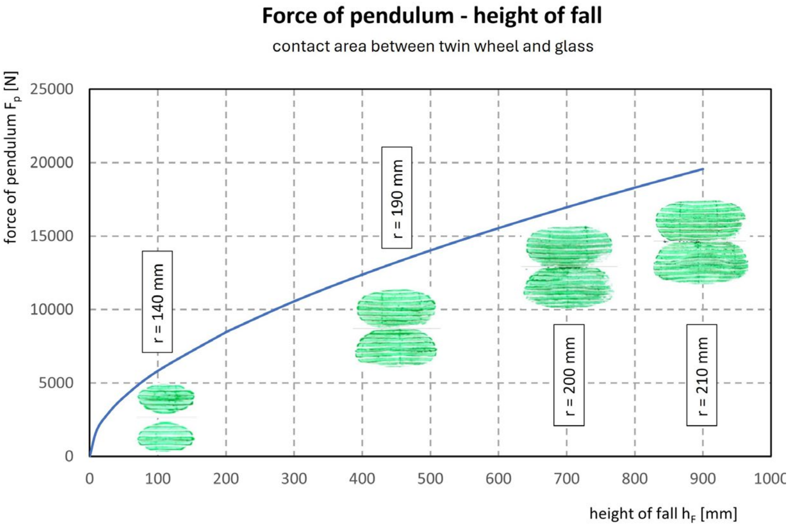

Fig. 7: Contact area between twin wheel and glass in respect to the force of pendulum (Neugebauer J. Schachner K.).

7. Results of numerical Simulation

Considering the boundary conditions described above, parametric studies were carried out using a simple transient finite element program (SJ Mepla). First, the support conditions were systematically varied, followed by an investigation of different glass heights.

7.1. Variation of elastic supporting system

As part of a parametric study, the model presented in Figure 6c was adopted and the stiffnesses of the elastic line support were systematically varied. The motivation for this analysis was the uncertainty regarding the adequate representation of the different materials and geometries present in the real support system within the finite element model. The glass pane was modelled with a height of 1000 mm, a width of 2000 mm, and a laminated safety glass build-up consisting of 2 × 8 mm heat-strengthened glass (HS glass).

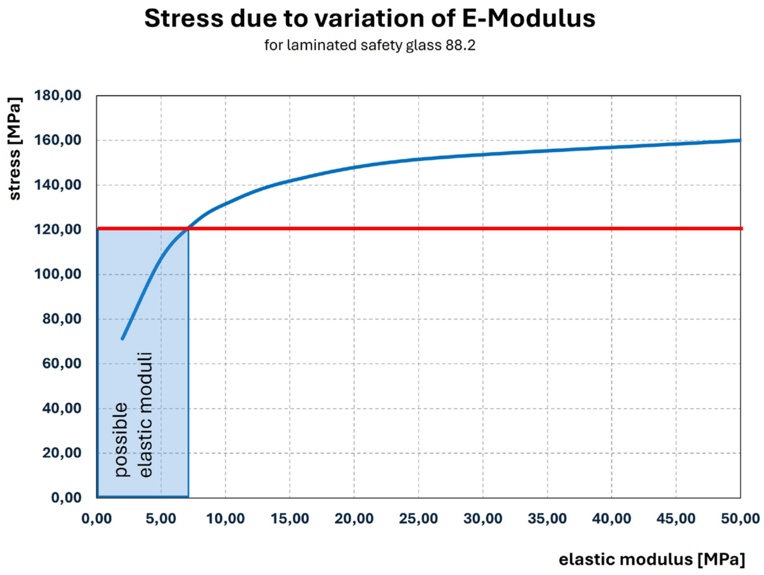

Fig. 8: Results of Finite Element Calculation of Variation of supporting systems.

The results indicate that, for a balustrade glazing made of laminated safety glass (2 × 8 mm heat-strengthened glass), the verification can be carried out using an elastic line support. This requires the support to be modelled with a width of b = 20 mm and a thickness of h = 5 mm, and an elastic modulus was varied between of E = 5 MPa to 50 MPa. The model is shown in Figure 6c. The results show that, with assumed elastic moduli of E < 7.5 MPa, verification of the short-term strength of heat-strengthened glass (HS glass) in accordance with ÖNORM B 3716-3 (f = 120 MPa) can be achieved, as illustrated by the blue highlighted area in Figure 8.

7.2. Variation of Hight of the Glass

As part of a further parametric study, the model presented in Figure 6c was adopted and an elastic modulus of E = 5 MPa was assigned to the elastic line support. The objective of the investigation was to systematically analyse the influence of the glazing height on the resulting stresses. Different glazing heights may arise, for example, from mounting the balustrade on a concrete plinth, as illustrated in Figure 9 with plinth heights of 125 mm and 250 mm. The results show that as the glass height decreases, the overall stiffness of the system increases. Due to the reduced deceleration path during pendulum impact, the resulting impact force increases, leading to higher stresses in the glazing. Figure 9 clearly demonstrates that the stresses increase significantly as the glass height is reduced. It can therefore be concluded that verification for a balustrade height of 1000 mm cannot be directly transferred to lower heights.

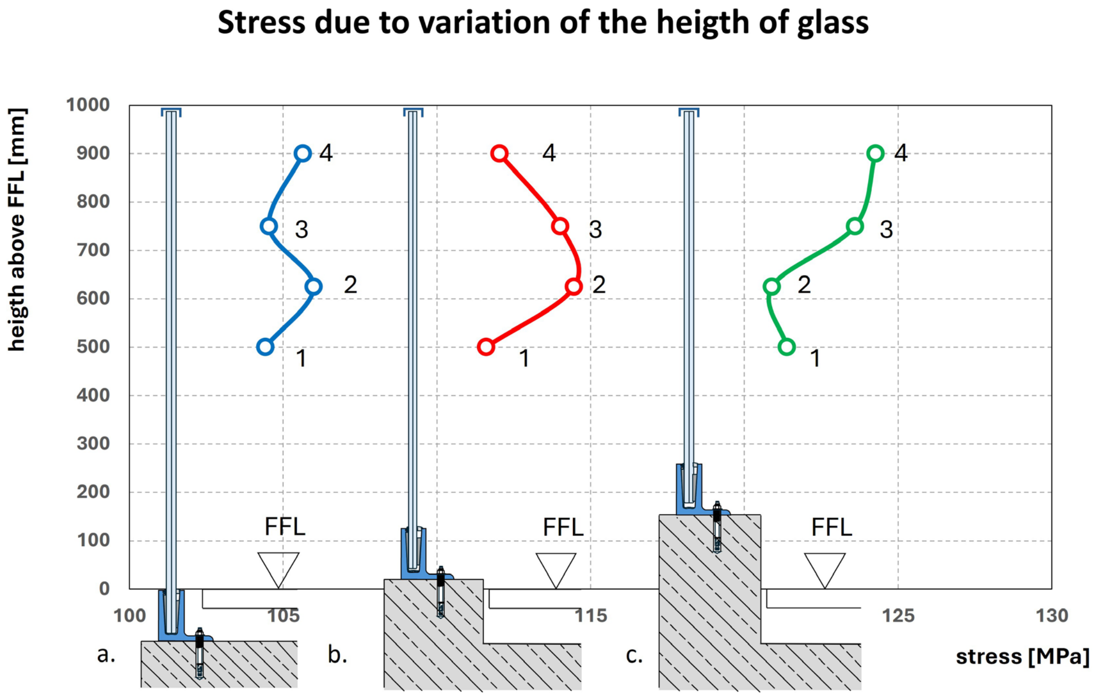

Fig. 9: Results of Finite Element Calculation of Variation of height of glass.

8. Summary

In summary, it can be stated that the dynamic verification by means of a pendulum impact represents a highly complex and strongly transient process occurring within a very short time span. The interaction between the impact body, the glazing, and the support system results in a nonlinear behaviour governed by contact and material effects, placing high demands on both experimental testing and numerical modelling as well as on the interpretation of the results.

The starting point of the present investigations was the comparison between the experimental pendulum impact test and the numerical simulation. While verification for a balustrade glazing could be successfully achieved experimentally, it could initially not be confirmed by numerical analysis. This discrepancy highlights the sensitivity of the system to modelling assumptions, particularly with regard to support stiffness, contact definition, and boundary conditions.

Furthermore, the experimental verification according to EN 12600 raises a fundamental question: can verification be considered successful if the glazing itself remains intact, but the supporting structure fails? This issue concerns not only the numerical representation of the system, but also the normative and structural assessment of the overall load-bearing behaviour.

Since EN 12600 is primarily intended for the classification of safety glass based on standardized test specimens, its suitability for the assessment of fall-protection glazing systems should be critically examined. The question arises whether the results obtained under standardized testing conditions adequately represent the actual behaviour of the wide variety of glazing systems used in practice, each characterized by different support conditions, boundary conditions, and structural configurations.

A further important aspect is that the forthcoming EUROCODE largely delegates the detailed requirements and verification procedures for fall-protection glazing to the national standardization bodies through the National Annexes. This raises the question of the extent to which a harmonized

European approach to the assessment and design of such glazing systems can actually be achieved. The anticipated national differences in requirements and verification procedures may hinder the establishment of a uniform European framework and reduce the comparability of verification results between member states.

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