Structures 87 (2026) 111763

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Structural design of balustrades: Code compliance, cross-section requirements and case studies

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ARTICLE INFO

Keywords:
Safety
Glass
Steel brackets
Structural analysis
Design
Balustrade
Vertical cantilever
Glass codes
International design standards

ABSTRACT

Glass balustrades, typically designed as vertical cantilever structures with rigidly restrained bases, are a prominent feature in buildings, especially in elevated areas such as balconies, staircases, and rooftops, where safety and visual transparency are critical. While offering significant aesthetic and transparency, the inherent brittleness of glass necessitates meticulous structural design to ensure user safety and overall system integrity, as potential customer fallout or other discomfort should be avoided.

In view of these, this paper provides a technical synopsis of the structural design principles, material specifications, and code compliance requirements for glass balustrades. It examines major international standards, with particular focus on limit-state criteria. It also addresses comparison of well-known design standards. The research methodology shifts beyond a descriptive overview, instead focusing on a quantitative assessment of how different safety factors and displacement limits influence the structural thickness requirements of laminated glass. The comparative analysis shows that the required glass thickness may vary by 20–30% depending on the adopted safety factors, while maximum deflection limits range from Span/60 to L/250 across standards. In the presented case studies, maximum glass stresses ranged from 7.3 MPa to 37.8 MPa, and deflections ranged from 3.59 mm to 15 mm, all within code-prescribed limits. The findings help engineers identify conservative biases or safety gaps in current regulations, thereby contributing to the development of more robust, evidence-based global standards.

1. Introduction

Balustrades are essential structural safety components in buildings, primarily designed to prevent accidental falls from elevated spaces such as balconies, staircases, mezzanines, and halls. Beyond their critical life-safety function, balustrades also contribute significantly to the architectural character and aesthetic appeal of built environments. Traditionally fabricated from timber, wrought iron, or mild steel, balustrade design has evolved in response to advancements in architectural design, material technologies, and increasingly stringent safety regulations.

Over the past two decades, the use of glass balustrades has grown substantially due to their ability to provide visual transparency, maximize daylight penetration, and support minimalist architectural profiles. These characteristics align closely with contemporary design philosophies and the growing emphasis on occupant well-being and visual connectivity.

However, using glass as a structural material poses distinct challenges. Unlike ductile materials such as steel, glass is inherently brittle, offering little to no warning before failure. As a result, the structural design of glass balustrades must rigorously address strength, post-breakage behavior, and serviceability criteria. Studies by various researchers [1–4] and guidance from the Institution of Structural Engineers [5] underscore the importance of considering residual strength, edge stability, and interlayer performance in laminated glass systems. Additionally, finite element modeling has become a widely adopted method for analyzing complex load paths and glass-to-structure connections in such systems.

The design and verification of balustrades are governed by a range of national and international standards, each specifying minimum design loads, load combinations, deflection limits, and material performance criteria. Key standards include:

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https://doi.org/10.1016/j.istruc.2026.111763
Received 19 January 2026; Received in revised form 8 March 2026; Accepted 30 March 2026

- AS/NZS 1170.1 (Australia/New Zealand) – Structural design actions, imposed loads [1]
- AS 1288:2006 Glass in buildings: Selection and installation [2]
- BS 6399–1:1996 Loading for buildings (UK) [3]
- BS 5950 Structural use of steelwork in buildings [4]
- IBC 2018 International Building Code (USA)
- EN 1991 & EN 1993 Eurocodes for actions on structures and steel design [5,6]
- CNR-DT 210/2013 (in Italian) Guide for the Design, Construction, and Control of Buildings with Structural Glass Elements [7].
- CEN/TS 19100:2021 "Design of glass structures" [8–10]

Additional research by Chan [11] and the European standard [9,12] provides analytical approaches and test methodologies for evaluating glass structures under uniformly distributed and point loads. These studies also emphasize the critical role of anchorage systems, mechanical or chemical, which must be validated under both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) conditions to ensure the balustrade assembly acts as a unified structural element.

This paper presents a comprehensive review of existing design methodologies, material specifications, and code compliance requirements for balustrades, with a focus on glass-based systems. It includes detailed case studies from several projects, featuring modeling approaches, load assessments, and component-level analyses across three balustrade types. The results are benchmarked against relevant standards and discussed in the context of best practices and emerging trends in transparent structural design.

The primary objective of this research is to conduct a critical analysis of international structural standards, specifically the Australasian, British, American, and European frameworks, to identify inconsistencies in safety philosophies regarding glass balustrades. While professional practice often relies on local codes, this study fills a gap in the literature by evaluating how varying load combinations and limit-state definitions (ULS, SLS, and PFLS) affect the material efficiency and perceived safety of cantilevered systems. By applying these diverse standards to six distinct real-world case studies, this paper establishes a benchmark for cross-border compliance and proposes a harmonized approach to post-fracture redundancy [8].

2. Material specifications

The performance, durability, and safety of a balustrade system are fundamentally influenced by the materials selected for its construction. Proper material selection ensures the system can resist imposed loads, endure environmental exposure, and maintain structural integrity throughout its service life. This section outlines the primary materials commonly used in balustrade systems, specifically glass, structural steel, stainless steel, aluminum, and anchorage components, along with their relevant mechanical properties and applicable code requirements.

Table 1 summarizes key material properties critical to balustrade design, including modulus of elasticity (stiffness), yield strength, and density. Structural steel grades such as S275 and S355, as well as aluminum alloy 6061-T6, are frequently used for posts, handrails, and connection brackets due to their favorable strength-to-weight ratios. In environments requiring enhanced corrosion resistance, such as marine or sanitary applications, stainless steel 316 is preferred.

Toughened (tempered) glass is typically used as the primary infill element due to its high compressive strength and fracture behavior. To improve safety in the event of breakage, laminated glass systems incorporate interlayers such as polyvinyl butyral (PVB), ionoplast (SGP), or ethylene-vinyl acetate (EVA). While these interlayers do not significantly increase the glass's structural stiffness, they play a vital role in ensuring post-breakage integrity, occupant safety, and long-term durability of the glazing system [13–16].

2.1. Glass

Glass is a brittle, non-ductile material, and its use in structural applications such as balustrades requires strict adherence to relevant national and international standards. The two most commonly used types in these applications are toughened (tempered) glass and laminated glass. Laminated glass, which consists of two or more glass layers bonded with interlayers, is particularly valued for its post-breakage integrity and is often mandated in public spaces or high-risk environments where safety is paramount. A typical configuration in balustrade systems is 10 mm to 19 mm clear toughened monolithic or laminated glass, which exhibits a modulus of elasticity (E) of approximately 70,000 MPa and a shear modulus (G) of 30,000 MPa, reflecting its stiffness and resistance to deformation under loads. It also has a Poisson's ratio (μ) of 0.22 and a unit weight (γ) of 27 kN/m^3 , which are standard material properties used in structural analysis and design. The allowable stress (σ_{allow}) is 50 MPa in accordance with AS 1288:2006.

Additionally, it exhibits a thermal expansion coefficient (α) of 9×10^{-6} /°C, which is relevant for assessing dimensional changes due to temperature variations. Laminated glass (e.g., 10.38 mm or 13.52 mm) includes interlayers such as PVB or SGP for safety. Heat-soaked toughened glass is preferred in high-occupancy zones to reduce the risk of spontaneous breakage. Ethylene-Vinyl Acetate (EVA) is increasingly specified for balustrades in harsh environments, such as coastal zones, tropical climates, and high-UV-exposure areas, due to its superior moisture resistance, UV stability, and thermal adaptability compared to traditional PVB [17,18].

2.2. Interlayers for laminated glass

In laminated glass systems, the choice of interlayer significantly impacts structural performance, particularly in post-breakage scenarios [2], Interlayers are essential for maintaining the integrity of the glass assembly after fracture, providing safety and load transfer even when the glass is compromised. PVB (polyvinyl butyral) is the most commonly used interlayer, known for its good optical clarity and moderate post-breakage strength [19]. It is widely used in architectural applications where standard safety performance is sufficient. SGP (SentryGlass), an ionoplast interlayer, offers five times the tear strength and up to 100

Table 1
Summary of material properties.

Material	Modulus of Elasticity E (MPa)	Design Strength Parameter (MPa)	Density (kN/m^3)	Typical Use
Glass (Toughened)	70,000	50 Allowable bending stress (σ_allow)	27	Panels, infill
Steel (S275)	210,000	275 Yield strength (fy)	78.5	Posts, brackets, rails
Steel (S355)	210,000	355 Yield strength (fy)	78.5	Higher-strength structural components
Stainless Steel 316	~200,000	230 Yield strength (fy)	78.5	Exterior, marine & hygienic areas
Aluminum (6061-T6)	69,000	240 proof stress strength (f0.2)	27	Lightweight modular handrails
PVB (Interlayer)	~0.4 – 1	–	~1.1 – 1.2	Standard safety interlayer (glass bonding)
SGP (Interlayer)	–~25	–	~1.1 – 1.2	High-strength interlayer for structural glass
EVA (Interlayer)	–~10 – 15	–	~1.1 – 1.2	UV-resistant interlayer for outdoor glazing

Note: The design strength of glass is highly dependent on factors like thermal treatment (annealed, heat-strengthened, or toughened), surface finish, and load duration. Glass values represent allowable bending stress under short-duration loading per AS 1288. Steel values represent characteristic yield strength (fy).

times the stiffness of PVB. It significantly improves residual load-bearing capacity, making it ideal for structural glazing and balustrade applications where high post-breakage performance is critical. EVA (ethylene-vinyl acetate) provides similar mechanical strength to PVB but with greater UV resistance, moisture tolerance, and flexibility, making it well-suited for exterior and humid environments [20,21].

Typical shear modulus values at 20°C are:

- PVB: 0.4–1 MPa (long-term), 5–10 MPa (short-term)
- SGP: 20–30 MPa
- EVA: 10–15 MPa

While the interlayer itself does not possess the structural modulus of glass, its shear coupling effect is fundamental to the system's effective thickness. Under sustained or high-temperature loading, shear transfer through a standard PVB interlayer may diminish, leading the glass plies to act independently (layered behavior). Conversely, Ionoplast interlayers (e.g., SGP) provide high shear stiffness, allowing the laminate to approach the behavior of a monolithic section, thereby significantly increasing the calculated Moment of Resistance and reducing deflection.

2.3. *Structural steel*

Steel is widely used for balustrade posts, handrails, and brackets due to its high strength, fabrication flexibility, and cost-effectiveness [4,22]. Structural steel used in balustrade systems is commonly specified as S275 or S355. S275 has a yield strength (fy) of 275 MPa for thicknesses up to 16 mm and an ultimate strength (f_u) of approximately 430 MPa, while S355 offers enhanced performance with a yield strength of 355 MPa and an ultimate strength of around 510 MPa. Both grades share a Poisson's ratio (μ) of 0.3, a modulus of elasticity (E) of 210,000 MPa, and a density (γ) of 78.5 kN/m^3 . Their thermal expansion coefficient (α) is 12×10^{-6} /°C, relevant for thermal loading considerations [23].

2.4. *Stainless steel*

Stainless steel is often preferred to ordinary steel for its durability, aesthetic appeal, and low maintenance in high-corrosion environments (e.g., coastal or medical settings) [24]. Stainless steel grades 304 and 316 are commonly used in balustrade systems for their strength and corrosion resistance. Both grades provide a yield strength (f_y) of 210–230 MPa and an ultimate strength (fu) of 520–620 MPa. While Grade 304 offers good corrosion resistance suitable for most indoor and sheltered applications, Grade 316 provides excellent resistance, making it ideal for marine or highly corrosive environments. Both grades are available in brushed or mirror finishes, providing aesthetic flexibility for architectural applications [25].

2.5. *Aluminium alloys*

Aluminium alloys (e.g., 6061 and 6063-T6) are lightweight, corrosion-resistant metals suitable for modular balustrades and architectural railing systems [26]. Aluminium alloy 6061-T6, commonly used in balustrade systems, offers a conventional yield strength (f_y) of approximately 240 MPa and an ultimate strength (f_u) of around 270 MPa. It has a modulus of elasticity (E) of 70,000 MPa and a density (γ) of 27 kN/m^3, making it a lightweight yet structurally capable option. Known for its high corrosion resistance, especially when anodized, 6061-T6 is well-suited for exterior and modular railing applications where weight reduction and durability are important [27].

2.6. *Anchor bolts and fixings*

Anchorage systems are critical for transferring loads from the balustrade into the supporting concrete or structural framework. Among the various options available, chemical anchors are particularly well-suited for glass balustrade applications due to their high load-bearing capacity and minimal disturbance to the base material during installation [28–30]. Commonly used systems, such as Hilti M12 or M10 chemical anchors, offer robust performance and are widely adopted in practice. These anchors typically incorporate steel elements of grade 5.8 or higher, conforming to EN ISO 898–1, and are intended for use in concrete substrates with a minimum compressive strength of C25/30. The design, qualification, and performance of chemical anchors are governed by the European Technical Assessments (ETA) and EOTA Technical Report TR 029, which provide testing protocols and design criteria for post-installed fasteners. Adherence to manufacturer-specific installation tolerances is essential to ensure structural reliability, maintain safety margins, and achieve compliance with applicable regulations [31,32].

2.7. *Lifecycle and recyclability*

Material selection significantly impacts sustainability:

Aluminum (6061-T6):

Recyclability: 95% energy savings vs. primary production (ISO 14040). Anodizing extends lifespan but complicates recycling.

Carbon Footprint: ~8.24 kg CO_2/kg (cradle-to-gate), offset by durability in modular systems (Case Study 5).

Steel (S275/S355):

Recyclability: Infinite recyclability with EAF (Electric Arc Furnace) processing, but coatings (e.g., powder coating) require removal.

Carbon Footprint: ~1.85 kg CO_2/kg (lower than aluminum but heavier).

Glass:

Closed-Loop Recycling: Cullet (recycled glass) reduces melting energy by 20% (ASTM C1492). Laminated glass requires an interlayer, which currently limits recycling rates.

Designers should balance structural needs with environmental targets, leveraging tools like EN 15804 for lifecycle assessment.

The material properties outlined in Table 1 directly influence the selection of installation methods (Fig. 3) and handrail configurations (Fig. 4) mentioned in the forthcoming section. For instance, the high stiffness of S355 steel justifies its use in floor-mounted channels, while the post-breakage performance of laminated glass guides frameless balustrade designs.

3. Design methodology

Balustrades must comply with both architectural regulations and structural engineering standards to ensure safety, durability, and occupant comfort. Structurally, balustrade systems must meet the performance criteria defined by the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS), addressing both strength and deformation limits under design loads.

The structural integrity of glass balustrades is evaluated through three distinct limit states, moving from deterministic strength checks to redundant safety assessments:

- Ultimate Limit State (ULS): Ensures the system resists peak design loads (wind, crowd pressure) without structural collapse.
- Serviceability Limit State (SLS): Limits deflections to prevent user discomfort or instability, typically restricted at L/65 or 25 mm, depending on the adopted code.
- Post-Fracture Limit State (PFLS): A critical safety requirement for laminated glass. It dictates that the system must retain residual stability after the accidental breakage of one or all glass plyes. This state ensures the balustrade remains a protective barrier, held together by the interlayer, until it can be replaced.

In addition to structural requirements, building codes, accessibility standards, and fire safety regulations impose constraints on elements such as minimum height, maximum opening dimensions, and load resistance. These parameters vary based on factors including building classification, occupancy type, and intended use, and are essential to ensuring both functional performance and compliance with regulatory obligations.

To complement the analytical and experimental investigations, simplified mechanical models were developed to capture the influence of restraint conditions on the structural response of glass balustrades. These models consider both quasi-static lateral loading and soft-body impact scenarios, which are critical for assessing occupant safety and compliance with regulatory standards. The simplified representations treat the glass panel as an elastic plate or beam element, supported by discrete or continuous restraints that mimic realistic boundary conditions such as point clamps, continuous channels, or hybrid fixings. By varying support stiffness in the models, the effects of flexibility, partial restraint, and frame glass interaction could be evaluated. These models provide a practical tool for predicting global displacement behavior, stress distributions, and failure thresholds under different load cases, offering insights that align with full-scale test observations and complement finite element simulations [33,34].

3.1. Architectural requirements

Minimum height requirements, opening limitations, and design loads for balustrades vary by jurisdiction, building classification, and intended use. These parameters are governed by international standards and national building regulations, including the International Building Code (IBC), AS/NZS standards, and the UK Building Regulations.

Table 2 summarizes the minimum required balustrade heights for different occupancy types, as prescribed by these codes. For example:

- Residential balconies generally require a minimum balustrade height of 1000 mm.
- Public and commercial spaces such as roof terraces, observation decks, or balconies typically require increased protection, with minimum heights of 1100–1200 mm.
- Staircases have variable requirements: residential settings often mandate a minimum height of 865 mm measured from the nosing, while public stairways demand greater heights for enhanced safety.

Fig. 1 depicts a frameless glass balustrade without handrails. It is important to note that the balustrade configuration shown in Fig. 1 does not include a handrail. This detail is critical for evaluating the post-fracture behavior of the glass panels, as the absence of a top restraint influences load redistribution and overall system stability following glass breakage. The design thus represents an unframed glass balustrade, which provides a conservative basis for verifying post-breakage performance in accordance with relevant standards.

The glass panel measures 965 mm wide and 1180 mm high above the finished floor level (FFL), with the base embedded 240 mm into the channel. The total height, from the bottom of the base to the top of the glass, is 1420 mm. Section BB illustrates the typical channel fixing method used in frameless balustrade systems, in compliance with AS 1288:2006 and EN 1991–1–1.

Table 2
Minimum balustrade height by use.

Type	Minimum Height	Code Reference
Residential Balconies	1000 mm	IBC 2018 §1015.2 / AS 1657 / UK BR/ CNR-DT 210/2013
Public Balconies	1100 mm	IBC 2018 / BS 6180:2011/ CNR-DT 210/2013
Staircases (residential)	865 mm (from nosing)	AS/NZS 1170.1 / BS 6180/ CNR-DT 210/2013
Staircases (public)	900 – 1000 mm	IBC §1011.11 / BS 6180/ CNR-DT 210/ 2013
Swimming Pools	1200 mm	AS 1926.1 / IBC / Local Pool Codes/ CNR-DT 210/2013
Roof Terraces	1100–1200 mm	BS 6180 / Dubai Code / NFPA 101/ CNR-DT 210/2013

The technical drawing shown in Fig. 2 is a detailed cross-section of a glass balustrade fixed directly to a finished floor, showing the structural components, dimensions, and fixings used in a high-specification installation.

Most codes stipulate that no openings in the balustrade, including gaps between glass panels or railings, should allow the passage of a 100 mm sphere to comply with child-safety provisions.

The growing preference for frameless and/or handrail attachment designs (Fig. 4) challenges traditional deflection limits, necessitating advanced FEM tools to validate minimalist systems.

The diagram in Fig. 3 systematically categorizes six standard methods for installing glass balustrades/handrails in architectural work. Each category branches into specific techniques, including angle cleat variations and C-beam applications. The hierarchical structure aids in selecting appropriate methods based on structural requirements and site conditions, with embedded installations typically used for flush floor finishes and wall-mounted options for space-constrained environments.

Fig. 4 shows five standard handrail integration methods, ranging from traditional post-supported systems to contemporary frameless designs. Each configuration shows distinct structural interfaces: posts for standalone applications, base shoes for wall-mounted systems, and spigots for pipe rail integrations. The frameless option highlights minimalist applications meeting IBC code requirements for barrier-free designs.

Note: Thermal expansion coefficients (Table 1) must be accounted for in channel/cleat spacing.

3.2. Structural limit states

ULS (Ultimate Limit State) ensures that the balustrade remains stable and does not collapse under extreme or accidental loading. The collapse limit state verifies the residual capacity after partial damage. The design must account for the worst-case combinations of dead load (DL), live load (LL), and potentially wind load (WL) or impact load. The following requirements must be satisfied:

- Structural members (glass, brackets, posts) must withstand:
  - Line loads along the top of the balustrade;
  - Point loads at specific vulnerable areas;
  - Uniformly distributed loads (UDL) across the panels.
- Anchorage and fixings must resist resultant reactions.

Table 3 provides the recommended deflection limits for key balustrade components to ensure both structural integrity and user comfort. Glass panels are generally limited to a deflection of span/60, as per AS 1288:2006 [35,36], to ensure sufficient stiffness to prevent excessive flexing under load. Steel brackets supporting structural elements are restricted to a more stringent span/180 limit in accordance with BS 5950–1:2000, [35] thereby minimizing movement and preserving alignment. Handrails, as user-contact elements, are designed with deflection limits ranging from span/100 to span/150, as recommended by the IStructE Guide, to provide a solid and comfortable user experience.

It should be noted that deflection limits vary significantly between codes. For example, AS 1288 specifies Span/60 for glass panels, whereas IBC limits deflection to L/240, and Eurocode adopts L/250 depending on occupancy. In this study, deflection checks were performed in accordance with the governing code for each case study.

Table 3 provides a concise summary of key considerations to ensure balustrade systems meet relevant safety standards and building codes. This checklist serves as a practical reference during design, specification, and review stages.

The structural performance of balustrade systems heavily relies on

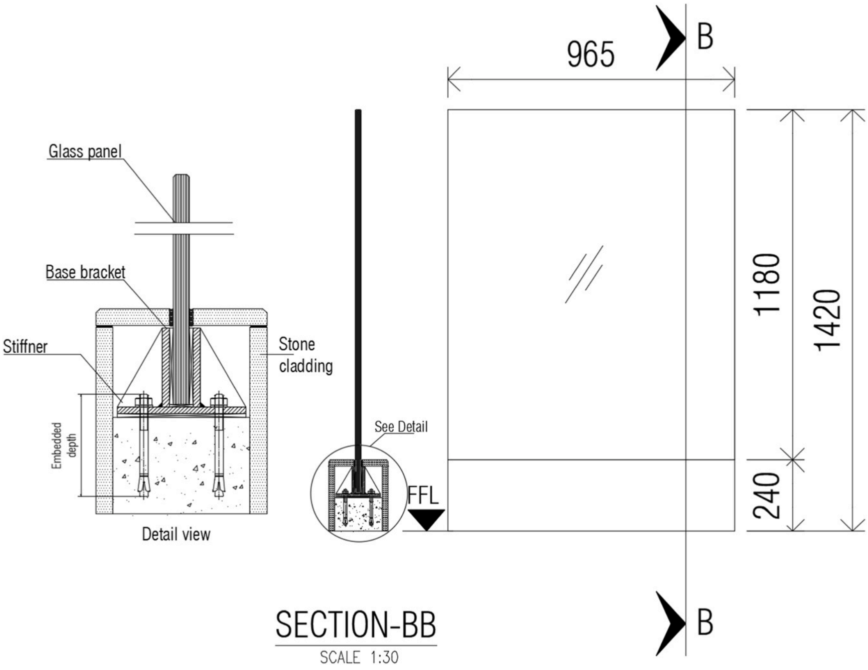

Fig. 1. Frameless glass balustrade showing elevation, embedded base channel, and labelled structural components.

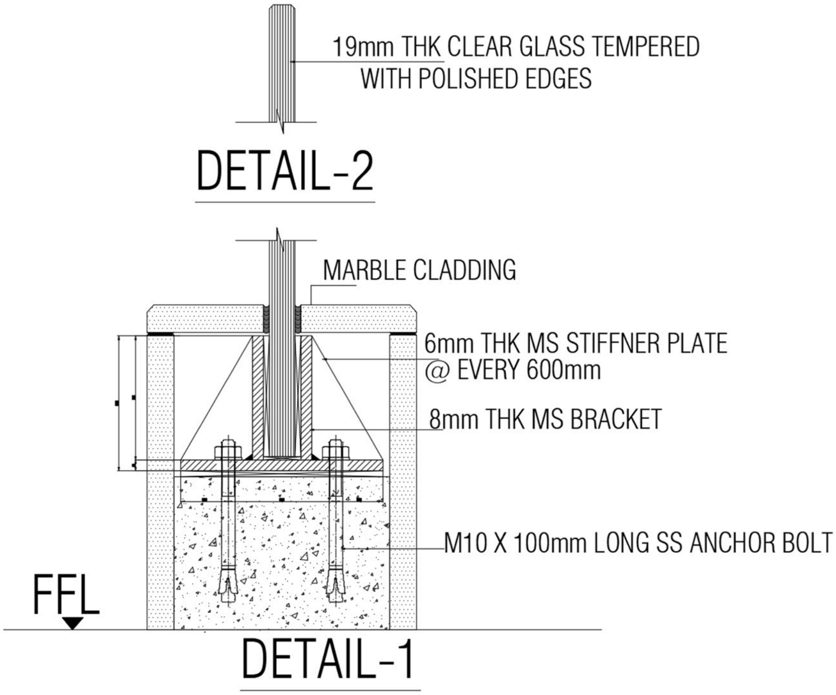

Fig. 2. Detail cross-section of a balustrade fixed on the floor.

the precise identification and application of relevant loading scenarios. These loads must accurately reflect the permanent and transient forces the system will encounter throughout its service life. Broadly, the loads considered in balustrade design fall into two primary categories: permanent actions (dead loads) and variable actions (live or imposed loads). In some instances, additional loads such as impact, wind, and thermal effects are also considered, particularly for exterior installations or those exposed to harsh environments. These additional loads are typically treated as special load cases and are analyzed separately.

3.3. *Failure modes and mitigation strategies*

Balustrade systems must account for site-specific risks beyond standard load cases. Key failure modes include:

- Anchor Corrosion:
  - o *Coastal/High-Humidity Zones*: Stainless steel 316 anchors (Table 1) outperform carbon steel but require periodic inspection for pitting. Case Study 2 (HMC Simulation Centre) validated M12 chemical anchors in saline environments.

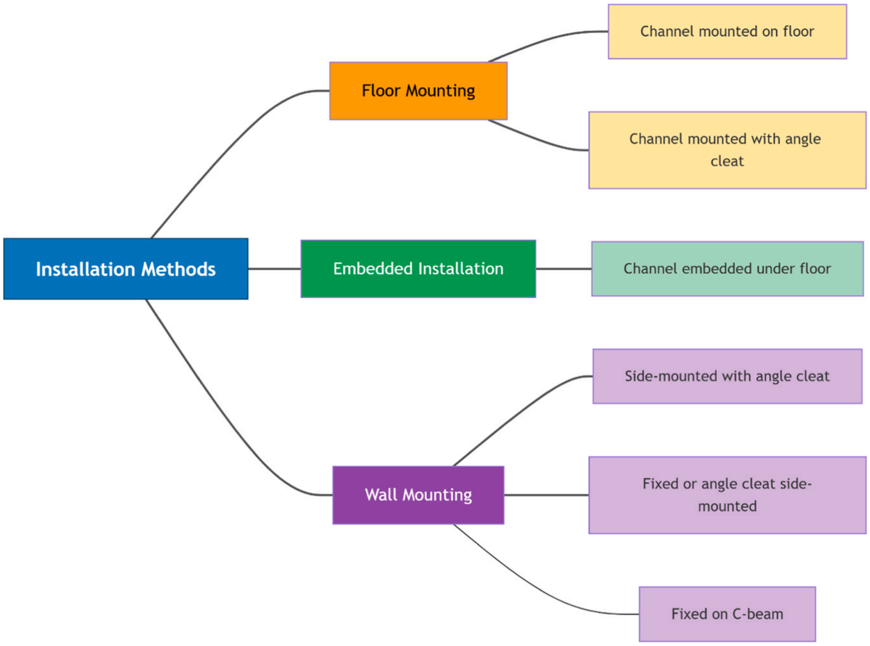

Fig. 3. Hierarchy of installation methods.

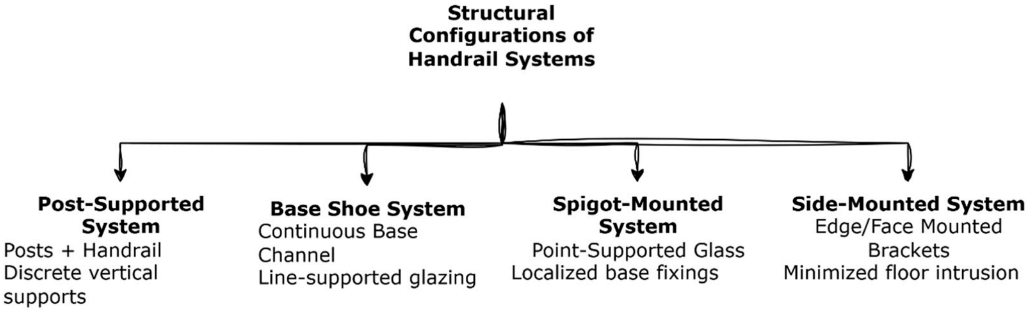

Fig. 4. Handrail structural configurations based on support and attachment mechanisms.

  - o *Mitigation*: Specify hot-dip galvanized steel or epoxy-coated anchors per ASTM A153/A123.
- Glass Edge Degradation:
  - o *Exposed Edges*: Micro-cracks from improper handling amplify stress concentrations.
  - o *Mitigation*: Polished edges + silicone edge covers (e.g., Dow SSG400E, Case Study 1) reduce fracture risk.
- Interlayer Delamination:
  - o *UV Exposure*: PVB interlayers degrade faster than SGP/EVA (Table 1).
  - o *Mitigation*: Use UV-stable EVA (2.6) for outdoor applications.

Risk assessments should align with ISO 13824 [45] for robustness, particularly in high-occupancy zones (e.g., stadiums in Case Study 6).

3.4. Load combinations

Structural design codes specify specific load combinations to account for the simultaneous occurrence of various load types, ensuring the structure remains safe under both extreme conditions and regular use. The primary load combinations are ULS (Ultimate Limit State) and SLS (Serviceability Limit State), with SLS focusing on deflection, vibration, and user comfort during normal use. Excessive deflection can result in user discomfort, visible cracks, or damage to finishes. These combinations are categorized into two main design states: the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

The ULS aims to prevent structural collapse or failure under rare but critical loading conditions. A representative ULS combination adopted in several standards (e.g., BS 5950 and IBC 2018) is 1.4DL + 1.6LL; however, partial safety factors vary between Eurocode, AS/NZS, and American codes. This ensures the structure has sufficient strength to withstand increased dead and live loads.

In contrast, the SLS focuses on performance criteria such as deflection, vibration control, and visual integrity under normal service conditions. The standard SLS combination is: $SLS = 1.0 \times DL + 1.0 \times LL$, ensuring the structure remains comfortable, functional, and visually acceptable during everyday use.

Together, the ULS and SLS load combinations form the foundation of a comprehensive structural design approach that balances safety with usability throughout the structure's lifespan.

3.5. Structural design workflow for balustrades

Fig. 5 illustrates a structured workflow for the structural design and verification of glass balustrade systems, encompassing modeling, code compliance, and performance evaluation. The process begins with the Modeling stage, where the system's geometric configuration is defined, and an initial selection of glass type and interlayer is made. This is followed by a simulation using finite element software [46,47].

In the Define stage, relevant material properties, design loadings,

Table 3
Comprehensive design and verification checklist for glass balustrades.

Design Aspect	Verification Requirement	Relevant Code(s)
Minimum Height	Compliance with occupancy-based height requirements	IBC / AS/NZS / BS 6180 [36,37]
Load Resistance (ULS)	Ultimate limit state load combinations and strength verification	AS/NZS 1170 / IBC / BS 6399 [1,3,38]
Serviceability (SLS) – Deflection Limits	Maximum allowable deflection under service loads	AS 1288 / BS 5950 [2,4]
Line and Point Load Verification	Concentrated and distributed load checks	IBC / Eurocode / AS 1288
Glass Strength Verification	Bending stress verification under design loads	ASTM E1300 [39,40]
Post-Fracture Limit State (PFLS)	Residual load-bearing capacity after glass breakage	EN 16612 / CNR-DT 210 / AS 1288 [12,41]
Interlayer Shear Modelling	Assumed shear modulus (short-term vs. long-term) and composite action verification	EN 16612 / CNR-DT 210
Anchorage Design	Anchor resistance (tension, shear, pull-out) and safety factors	EN 1992–4 / Manufacturer ETA [28,42]
Local Bearing & Contact Stresses	Verification of stress concentrations at clamps, spigots, and base shoes	EN 1993 / EN 16612
Impact Resistance	Pendulum or soft-body impact performance	EN 12600 [41]
Glass Breakage Classification	Safety glazing type (tempered, laminated, heat-strengthened)	AS 1288 / EN 16612 [12,43,44]
Thermal Movement & Edge Clearance	Allowance for thermal expansion and movement at supports	EN 1991 / Manufacturer Guidelines
Durability & Corrosion Class	Environmental exposure classification for metallic components	EN 1993 / ISO 9223
Connection & Detailing Verification	Verification of fixings, tolerances, edge distance, and constructability	Project Specification / Manufacturer Guidelines

and occupancy classifications are determined in accordance with the applicable standards. The third stage, analysis, involves assessing the structural behavior of the system, including the framing, fixings, and glass panels under both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) conditions.

Finally, the Demand-to-Capacity (D/C) check ensures that all components meet safety and performance criteria, with D/C ratios maintained below 1.0. This workflow provides a practical framework for engineers, supporting transparent and code-compliant balustrade design across various project types [48–50].

To ensure reproducibility, all case studies were analyzed using a semi-probabilistic approach. Material properties for Sodalime Silica Glass were assumed to be a characteristic bending strength (f_k) of 45 MPa for annealed glass and 120 MPa for tempered glass. Finite Element Analysis (FEA) was conducted using 4-node shell elements with a mesh sensitivity analysis to ensure convergence. The comparison across the six international codes was standardized by applying a uniform 1.0 kN/m line load to isolate the impact of the varying partial safety factors (γ_M and γ_G) inherent in each regional standard.

4. Load considerations

Dead load refers to the self-weight of all permanent components within the balustrade system. This includes the glass panels (e.g., 19 mm tempered glass, approximately 0.5 kN/m^2), handrails (typically made from stainless steel, aluminum, or mild steel), support brackets or posts, anchor systems, and any additional cladding or infill elements. Dead loads are calculated from material densities and geometric dimensions, often using structural analysis tools [51]. These values are crucial for foundational design and are generally considered constant over the structure's lifespan.

Live loads, or imposed loads, are transient forces that result from human interaction or movable objects impacting the balustrade system. These are typically applied at the top edge - commonly the handrail - and can be classified into several types:

- **Line loads**: Horizontal force applied uniformly along the handrail (e.g., 0.5–3.0 kN/m, depending on occupancy type);
- **Point loads**: Concentrated forces applied at specific locations (e.g., testing for localized strength);
- **Uniformly Distributed Loads (UDL)**: Applied to infill panels or glass surfaces to simulate general pressure.

Live loads vary by occupancy category and national codes and are essential for verifying both strength and serviceability under user interaction. These loads are integral to both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) checks and are often the dominant loading case for indoor balustrades. Table 4 lists typical line and point loads for balustrades across different applications, based on

Table 4
Typical Imposed Loads by Application.

Application	Line Load (kN/m)	Point Load (kN)	Code Reference
Residential	0.5	0.6	AS/NZS 1170 [52]
Public Balconies	1.5	1.5	BS 6399–1:1996; EN 1991–1–1 [53,54]
Retail/ Shopping	3.0	2.2	EN 1991–1–1:2002 [54]
Office Buildings	0.75	1.0	BS 6180; IBC [55,56]
Staircases (Public)	1.5	1.5	IBC 2018; AS/NZS 1170.1:2002 [56]

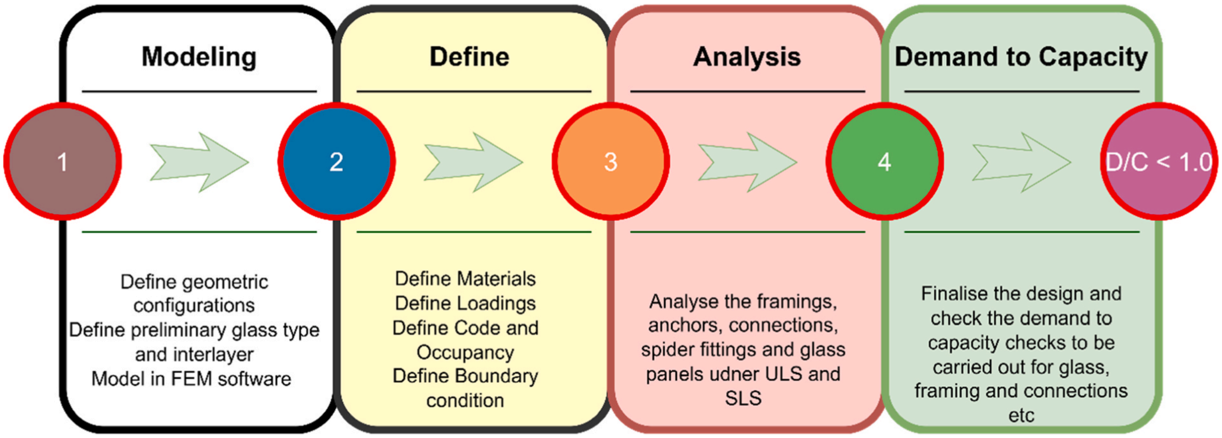

Fig. 5. Flowchart for the design of a balustrade.

international codes. Load values increase with public use, ranging from 0.5 kN/m for residential to 3.0 kN/m for retail, ensuring safety based on occupancy type.

The most critical load (line or point) must be used for design, not both simultaneously, unless specifically required by the local code. As shown in Table 4, public balconies require higher line loads (1.5 kN/m) than residential settings.

While dead loads (DL) and live loads (LL) are the primary design considerations for most indoor balustrade systems, several additional load cases may become critical depending on the installation's location and configuration. Wind loads (WL) are particularly relevant for exterior balustrades, such as those on balconies, terraces, or rooftops. These loads are typically calculated based on factors such as terrain category, building height, and exposure level. Wind loads are applied as suction or uplift pressures on glass panels, in accordance with AS/NZS 1170 [1,57] and EN 1991–1–4:2005 [5].

Thermal loads are another important consideration, arising from temperature-induced expansion and contraction, particularly in systems combining materials with differing coefficients of thermal expansion, such as glass and steel. To accommodate these movements and prevent stress accumulation, expansion joints or slotted fixings are recommended, particularly in long balustrades.

5. Code comparison

Table 5 summarizes the loading and deflection requirements for balustrade systems across major international codes.

Table 5 above highlights key insights into the loading and deflection requirements for balustrade systems:

- Dead loads are primarily influenced by the density of materials such as glass, steel, or aluminum profiles, as well as associated fixings.
- Live loads vary significantly by occupancy type and must be verified in accordance with applicable local codes.
- Wind loads, impact resistance, and thermal expansion should be considered in special-use or high-performance scenarios.
- Load combinations must comply with national or regional standards and address both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).
- Code comparisons help ensure that balustrade systems adhere to leading international safety and performance standards.

The span refers to the unbraced length between support or fixing points. For glass, particularly laminated types, the stiffness of the interlayer can significantly affect deflection behavior under SLS conditions.

Different international codes specify varying load intensities for balustrades, depending on occupancy type, location, and associated risk. Table 6 summarizes the prescribed design line loads applied at the top of balustrades across major codes. These load requirements increase with public exposure and risk levels, ranging from 0.5 kN/m in residential settings to 3.0 kN/m in high-traffic environments such as shopping centres. Such specifications ensure that balustrades can withstand typical lateral forces encountered in use, thereby maintaining safety and structural integrity across diverse applications.

Among the reviewed standards, Eurocode and CNR-DT 210/2013 tend to impose higher loads for public applications, while IBC adopts stricter deflection limits. AS 1288 places particular emphasis on glass-specific serviceability and post-breakage behavior.

In addition to line loads, balustrade design must also accommodate point loads, typically ranging from 0.6 to 1.5 kN, applied at critical locations such as corners or midspans, as well as uniform loads, commonly specified at 0.5 kN/m^2 on infill panels. Beyond structural strength and serviceability, several supplementary performance criteria must be addressed to ensure long-term safety and durability.

One such requirement is glass breakage resistance, particularly in laminated glass systems, where the interlayer must retain glass fragments and continue to support imposed loads post-fracture [2].

Impact resistance [12] is also essential, especially in public or high-traffic environments where accidental or deliberate impacts are more likely. Compliance typically involves pendulum or soft-body impact testing, as specified in EN 12600 [41].

Thermal expansion must be considered when designing with materials having differing coefficients of thermal expansion, such as steel and glass, to avoid stress concentrations, joint displacement, or failure. The incorporation of expansion joints or flexible fixings is recommended, particularly in outdoor or exposed environments [59].

Collectively, these criteria enhance the resilience and overall performance of balustrade systems under real-world conditions. For high-risk public areas, such as stadiums, a risk-based design approach is essential. This includes measures such as anchorage redundancy, anti-laceration glass edges, and post-failure containment, aligning with current best practices outlined in [53,54], and the ASTM E1300 [39,40] recommendations. The following case studies demonstrate how material selection, code-compliant load combinations, and installation methods converge in real-world applications

6. Case studies

To provide a consolidated overview of structural performance and code compliance, key parameters for assessing six case studies are identified and presented in Table 7. These projects span a diverse range of architectural applications, including residential staircases, high-rise balconies, and stadium installations, demonstrating the adaptability and reliability of glass balustrade systems when designed in accordance with international standards. The summary highlights essential factors, including glass type, analysis methods, governing load cases, maximum stress and deflection values, and compliance with structural safety criteria.

6.1. Case study 1: balcony handrail system

A comprehensive structural analysis was conducted for a 30-story mixed-use tower, approximately 100 m tall, with a focus on the performance and compliance of its glass balcony balustrade system. The system comprised 1100 mm high laminated tempered glass panels, specified as 8 mm + 1.52 mm PVB + 8 mm, mounted using S275 steel brackets and Hilti chemical anchors.

Table 5
Code Comparison for Balustrade Loading and Deflection.

Standard	Line Load (kN/m)	Point Load (kN)	Deflection Limit	Post-Breakage Requirement	Notes
AS/NZS 1170.1 [38]	0.5 – 1.5	0.6 – 1.5	Span/60	-	Use-based loading; Clause 3.3
AS 1288:2006 [2]	0.5 – 1.5	0.5 – 1.5	Span/60 (glass)	mandates PVB/SG	Clause 6.2, serviceability in 6.5.2
BS 6399–1:1996 [3]	0.74 – 1.5	1.0 – 1.5	Span/60	-	Table 1: conservative UK standard
IBC 2018 [58]	≥ 0.89	0.89 – 1.33	L/240	-	Clause 1607.8.1; stricter point loads
EN 1991–1–1 [5]	0.5 – 3.0	1.0 – 2.2	L/250	-	Depends on occupancy
CNR-DT 210/2013 (Italy) [7]	1.0 – 3.0	1.0 – 1.5	Span/60, max 20 mm	requires full-scale testing	Based on occupancy and SLS/ULS, post-breakage verification is mandatory

Table 6
Design loads on balustrades (Line Load at Top).

Occupancy Type	AS/NZS 1170.1 (kN/m)	BS 6399 (kN/m)	IBC 2018 (kN/m)	Eurocode EN 1991 (kN/m)	CNR-DT 210/2013 (kN/m)
Residential	0.5	0.74	0.89	0.5	1.0
Offices	0.75	0.74	0.89	0.75	1.0
Public Balconies	1.5	1.5	1.33	1.5	1.5
Shopping Centres	3.0	3.0	1.33	3.0	3.0
Staircases (residential)	0.5 – 0.75	0.74	0.89	0.75	1.0
Staircases (public)	1.5	1.5	1.33	1.5	1.5

Table 7
Summary of case studies – glass balustrade structural performance.

Case Study	Project / Location	Glass Type & Configuration (mm)	Analysis Tool	Critical Load Case	Max Stress (MPa)	Max Deflection (mm)
1	Balcony Handrail	8 + 1.52 PVB + 8 laminated	SAP2000	Wind (2083.5 Pa)	37.8 MPa	14.7
2	Simulation Centre	19 clear tempered	Autodesk Robot	LL = 1.5 kN/m	< 50 MPa	15
3	SS Staircase Handrail (Residential)	Stainless steel tube sections	FEM model	LL = 0.73 kN/m	190 MPa	10
4	Podium Glass Staircase	12 + 12 + 12 treads, 15 + 15 balustrades	Autodesk Robot	LL = 1.5 kN/m + 4 kPa	7.3 MPa (glass)	3.59
5	Vertical Posts & Handrails	19 tempered glass	Autodesk Robot	LL = 1.5 kN/m^2	< 275 MPa (steel)	15
6	Sports Stadium	25.52 laminated tempered	Autodesk Robot	LL = 1.5 kN/m^2	32.3 MPa	10

Key material properties included:

- Glass: design stress of 72.3 MPa (allowable limit: 50 MPa), modulus of elasticity E = 70 GPa
- Steel: yield strength of 275 MPa, modeled with E = 205 GPa
- Anchors: Hilti HIT-HY 200-R with HIS-RN M10 bolts at 300 mm spacing

The design complied with multiple international standards, including BS 1063:2000, BS 6399, AS 1288:2006, EN 13474, and ASTM E1300.

The loading analysis identified the wind pressure of 2083.5 Pa per BS 6399 as the governing load case. The residential live load of 0.5 kN/m was secondary. Structural modeling [47] confirmed:

- Maximum glass stress: 37.8 MPa, within the allowable 50 MPa (Fig. 6);
- Deflection: 14.7 mm, below the span/60 limit (Fig. 7).

Bracket and base plate dimensions were optimized to 160 × 8 mm and 150 × 8 mm, respectively. Anchor bolt performance was verified using Hilti PROFIS software [30], while weld detailing specified 6 mm fillet welds staggered at 300 mm c/c. A 40 mm silicone bite using Ultraglaze SSG400E [60] was found adequate for resisting tensile forces.

The analysis validated full compliance with structural performance requirements, including strength, serviceability, and safety, particularly under wind-dominated conditions. This case study underscores the importance of integrated finite element modeling, material verification, and code-specific detailing in delivering reliable, high-performance façade systems in high-rise construction.

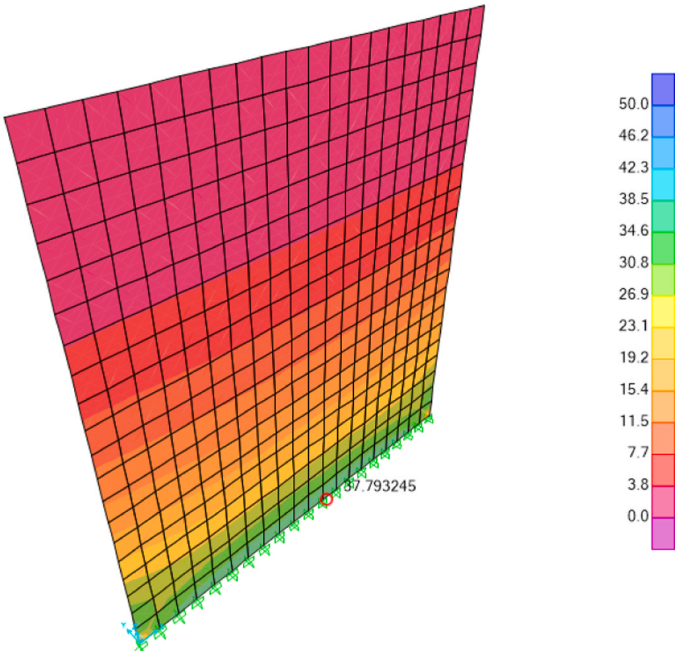

Fig. 6. Stress contour (Maximum stress at base 37.8 MPa).

6.2. *Case study 2: simulation centre*

This case study examines the structural design and verification of glass balustrade systems at the Simulation Centre, a healthcare training facility. The system, as shown in Fig. 8, employed 19 mm clear tempered glass, and the structural analysis was carried out using Autodesk Robot Structural Analysis 2014 [56] with design compliance based on AS 1288, BS 6399–1, and BS 5950–1. The project featured three distinct balustrade configurations: Type I, a cantilevered hanging glass system secured with M12 chemical anchors; Type II, a floor-mounted gravity-supported system using M10 chemical anchors; and Type III, a stair-mounted system with sloped fixing and M10 stainless steel fasteners. Design evaluation included verification under both Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The maximum glass stress under ULS was below the 50 MPa limit set by AS 1288, and the maximum deflection under SLS was 15 mm, remaining within the allowable limit of 19.8 mm (L/60). Brackets fabricated from S275 structural steel were found to operate within their yield capacity, and anchor forces were validated using Hilti ETA (European Technical Assessment) certificates. The findings affirm that 19 mm tempered glass, when used with S275 steel brackets and certified anchoring systems, provides a safe, code-compliant solution for public-use balustrades.

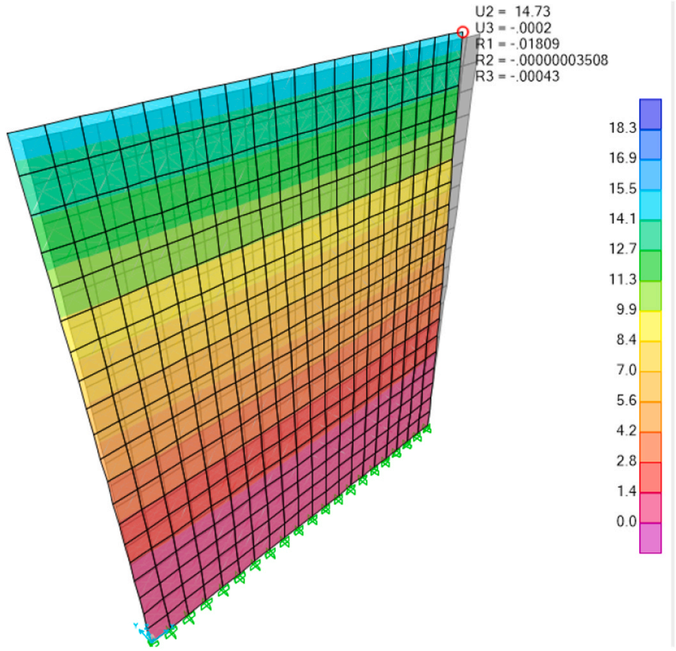

Fig. 7. Deformed shape (Maximum deformation at top of 14.7 mm).

6.3. *Case study 3 – stainless steel staircase handrail (Residential Building)*

A structural assessment was conducted for a stainless steel (SS) staircase handrail installed in a residential building. The evaluation involved developing a numerical model of the handrail system, incorporating tubular section profiles, and analyzing its structural behavior under both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) conditions.

A live load of 0.73 kN/m (as shown in Fig. 9) was applied in accordance with residential design requirements, and the system was assessed over a span of 2000 mm. Under ULS conditions, the maximum induced stress in the handrail reached 190 MPa (Fig. 10), remaining within the allowable limit of 220 MPa, thereby confirming structural safety. For SLS, the measured deflection was 10 mm, which is well below the allowable limit of 16.6 mm (calculated as L/120).

These results confirm that the stainless steel handrail meets both strength and serviceability criteria, demonstrating its structural adequacy and code compliance for residential applications.

6.4. *Case study 4: podium glass staircase*

The structural calculations for the podium glass staircase of a project were carried out to verify the safety and serviceability of both glass and steel components under applied loads. The staircase design incorporates laminated glass treads and landings composed of three 12 mm layers (12 +12 +12 mm), while the balustrades consist of double-laminated 15 mm glass panels. The entire structure is supported by a steel-framed system suspended by stainless-steel tension rods.

Numerical modeling and structural analysis were performed using Autodesk Robot Structural Analysis Professional 2014 (see Figs. 11 and 12), in accordance with the prescribed standards.

The analysis considered both dead loads (self-weight) and live loads, including a 1.5 kN/m horizontal load on the handrail and a 4 kPa imposed load on the landings and steps. The structural steel employed is S275 grade, with a yield strength of 275 MPa. Welding and anchorage details were specified in accordance with standard practices, using Hilti or Fischer anchor bolts.

The design was evaluated against both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) criteria. Under ULS conditions, stress checks confirmed that all components, glass treads, RHS steel members, I-sections, and tension rods, remained well within their allowable stress limits. For example, the maximum stress in the glass steps was 7.3 MPa, well below the 50 MPa limit, while the tension rods experienced a maximum stress of 28.5 MPa, well below the 220 MPa allowable limit (see Fig. 13).

Under SLS conditions, all deflections were within acceptable limits. The glass steps exhibited a deflection of only 1.1 mm, compared to the allowable 20 mm (based on span/60). Steel members such as RHS and I-sections also demonstrated minimal deflections, remaining well below the span/200 criterion. The glass components, including handrails and landings, performed within serviceability limits, with a maximum recorded deflection of 3.59 mm (see Fig. 14).

Additionally, a detailed analysis of anchor reactions at critical points, including the bottom channel, top landing, side connections, and top I-beam, confirmed that all anchorage systems can safely withstand the applied loads.

In conclusion, the entire staircase structure comprising glass components, steel framing, and anchorage systems meets the structural requirements for both ULS and SLS load combinations. The specified glass thicknesses (12 +12 +12 mm for treads and 15 +15 mm for balustrades) and anchor systems are deemed adequate. The design is structurally sound, fully compliant with relevant codes, and appropriate for its intended architectural application.

6.5. *Case study 5: vertical posts and handrails*

A structural evaluation was conducted for a glass balustrade system with posts spaced 1.55 m center-to-center and an overall height of 1.1 m. The system was modeled using Autodesk Robot Structural Analysis, incorporating appropriate support conditions for the glass panels, and evaluated under standard Ultimate Limit State (ULS) and Serviceability Limit State (SLS) load combinations.

A live load of 1.5 kN/m^2 was applied in accordance with relevant code requirements, as illustrated in Fig. 15. The analysis was performed using 19 mm clear tempered glass, with load combinations defined as follows:

- ULS: 1.4 × Dead Load + 1.6 × Live Load
- SLS: 1.0 × Dead Load + 1.0 × Live Load

The maximum deflection recorded was 15 mm, which remains within the allowable limit of 19.8 mm (based on Span/60). Stress analysis, presented in Fig. 16, confirmed that the induced stresses in all components remained below the permissible limits for S275 structural steel.

For connection detailing, 10 mm thick brackets were verified to be sufficient for both Type I (cantilevered) and Type II (floor-mounted) balustrade configurations under ULS and SLS conditions. M12 and M10 chemical anchors (Hilti or equivalent, minimum grade 5.8) were assessed and confirmed to be structurally adequate for Types I and II. Additionally, M10 stainless steel fasteners used in the assembly meet the necessary acceptance criteria, ensuring safety and compliance.

This assessment confirms that the proposed posts, handrails, bracket materials, and anchorage systems are structurally sufficient for the intended applications, ensuring compliance with applicable design codes and safety requirements.

6.6. *Case study 6: handrails with glass*

This case study assessed the structural adequacy of 25.52 mm-thick tempered laminated glass balustrades using finite element analysis. The analysis focused on evaluating induced stresses, deflections, and support reactions under both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) conditions. The glass was assigned a modulus of

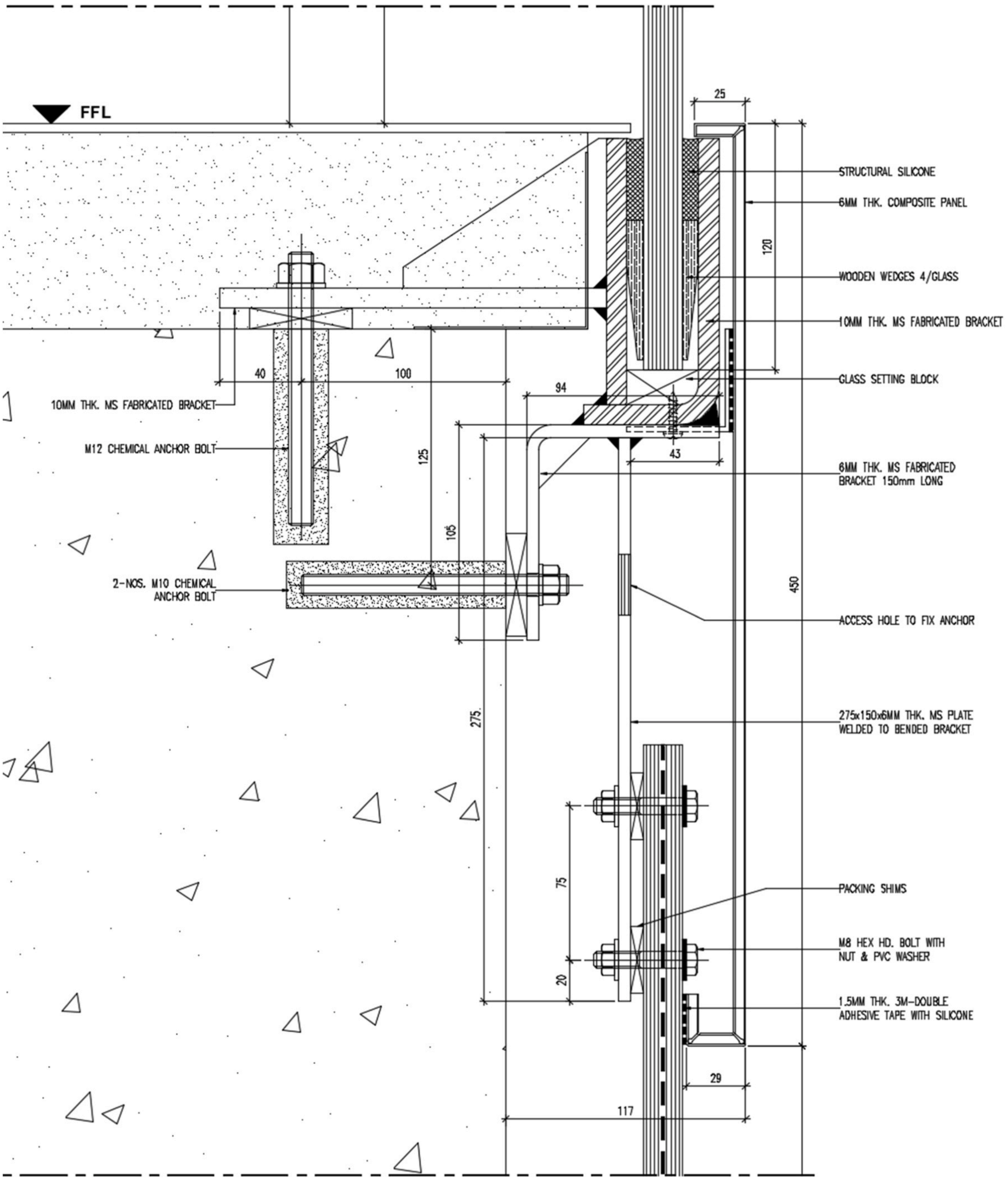

Fig. 8. Cross-section view of the frameless balustrade and fixing details.

elasticity of 70 GPa, a Poisson's ratio of 0.22, and an allowable tensile stress of 50 MPa. Structural steel components with a nominal yield strength of 275 MPa for elements up to 16 mm in thickness (see Fig. 17). The fixing system utilized M10 × 100 mm stainless steel bolts, and fillet welds were specified using E35 electrodes. A live load of 1.5 kN/m^2, applied at handrail height, was incorporated in accordance with BS 6399–1 (1996). Load combinations were based on BS 5950–1 (2000), with the critical design scenarios defined as:

- ULS: 1.4 × Dead Load + 1.6 × Live Load
- SLS: 1.0 × Dead Load + 1.0 × Live Load

Numerical results indicated a maximum stress of 32.3 MPa in the glass under ULS conditions (see Fig. 18), well within the allowable limit of 50 MPa. Under SLS conditions, the maximum deflection recorded was 10 mm, comfortably below the permissible limit of 19.8 mm (calculated as span/60). Support reaction analysis revealed maximum shear forces of 11.1 kN and axial forces of 5.28 kN at the top fastener locations.

These findings confirm that the proposed glass thickness and fixing system are structurally sufficient for their intended application at Al Ahli Stadium. The design complies with strength and serviceability requirements and meets the provisions of Australian and British standards, as well as relevant European pre-standards. Overall, the study verifies that 25.52 mm tempered laminated glass is suitable for use in all balustrade configurations considered for the project.

Across the six case studies, glass stresses ranged from 7.3 MPa to 37.8 MPa, with deflections consistently governed by serviceability rather than strength criteria. Wind loads dominated in high-rise

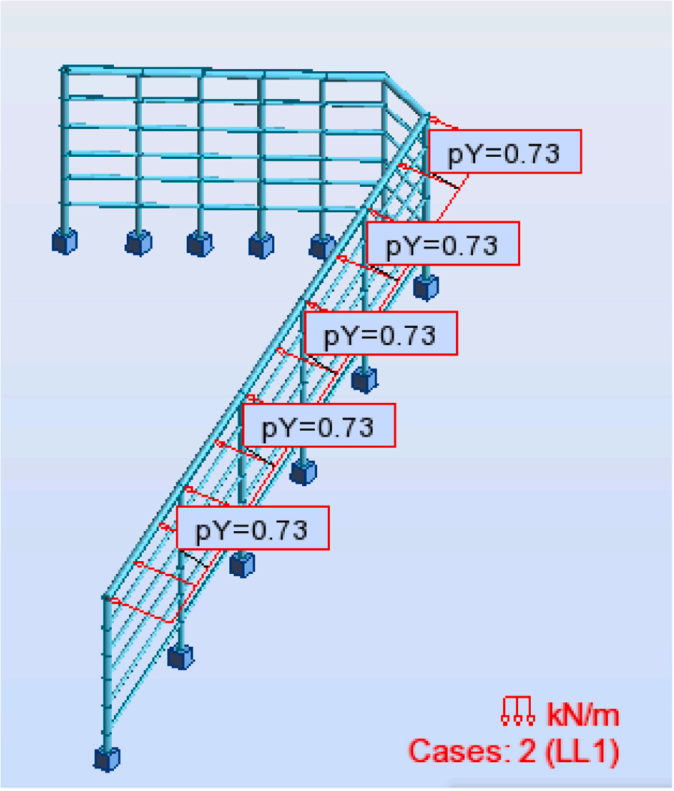

Fig. 9. Live Load on the handrail (0.73 kN/m).

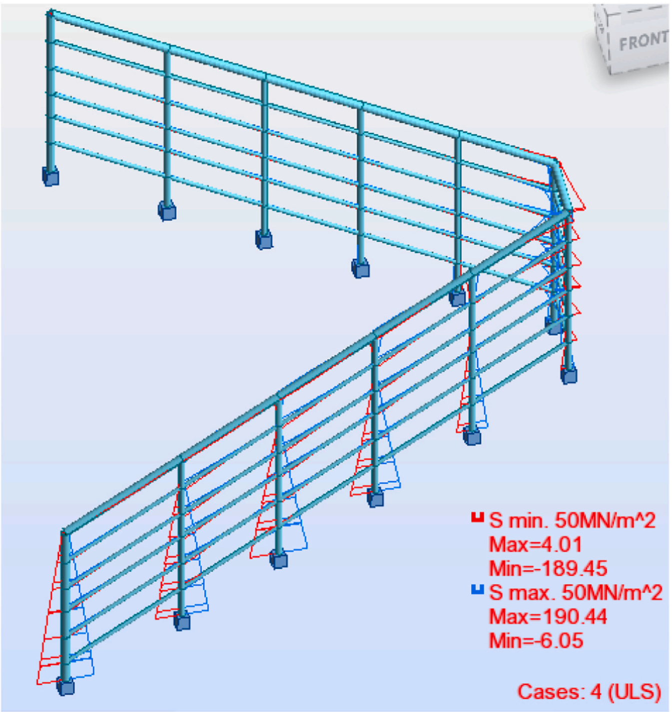

Fig. 10. Stresses in the handrail under ULS (190 MPa < 220 MPa).

applications, while line loads governed residential and stadium projects.

7. Future trends

The future of glass balustrade design is being transformed by emerging technologies and innovative materials that enhance structural performance, safety, and sustainability. Smart glass systems, such as electrochromic or thermochromic glazing, offer dynamic control over transparency and solar gain, improving occupant comfort and energy efficiency. Self-healing interlayers, including microcapsule-infused PVB and modified EVA, are being developed to autonomously repair minor cracks and delaminations, significantly extending the lifespan of laminated glass systems. Digital twin technology enables real-time structural monitoring through embedded sensors, allowing for predictive

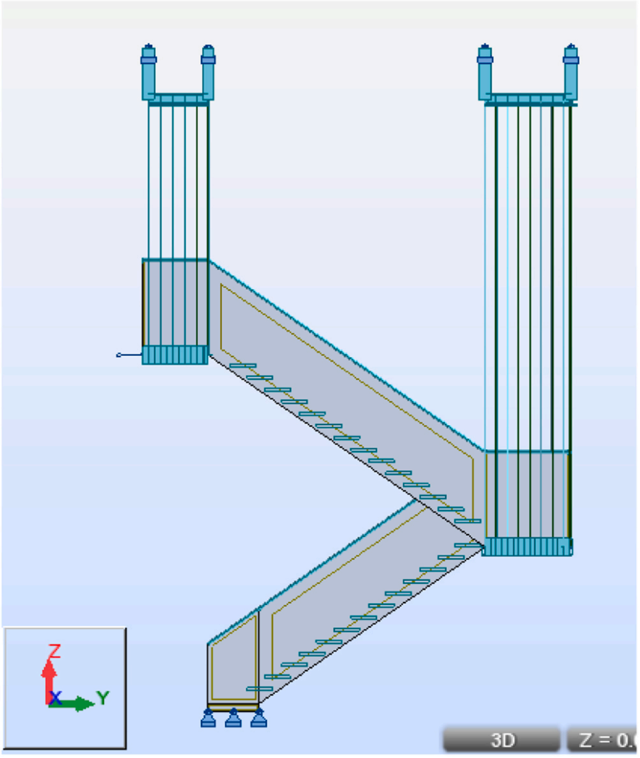

Fig. 11. Numerical model of the staircase.

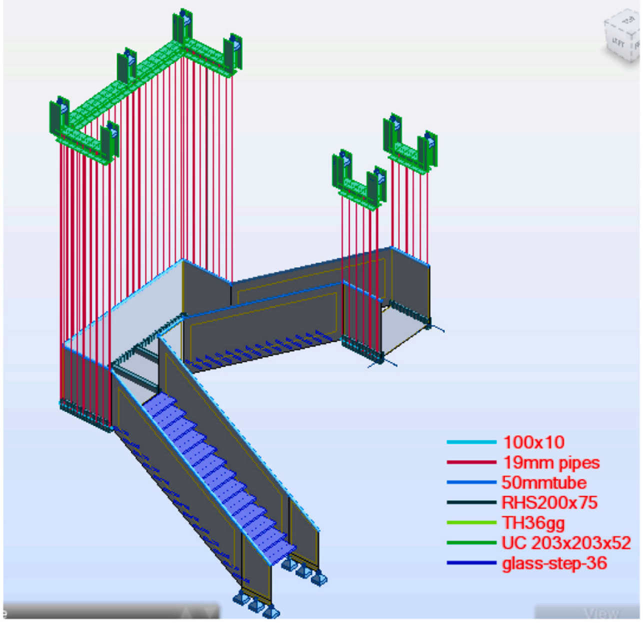

Fig. 12. Sections adopted for the staircase.

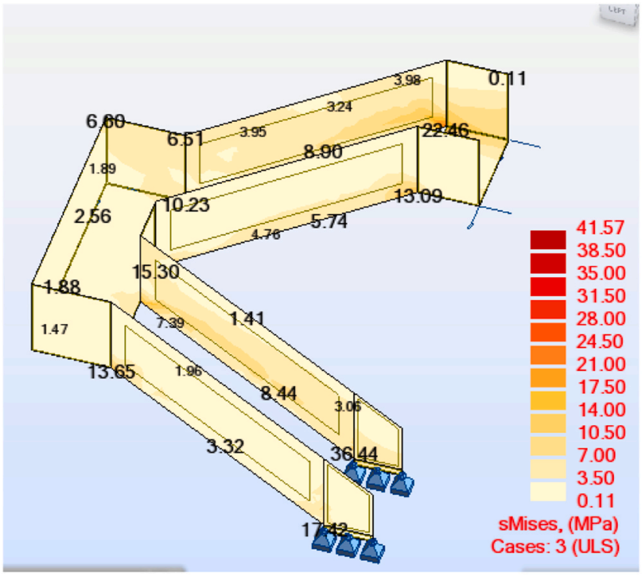

Fig. 13. Stresses in all the shell elements (handrails and landings) under ULS.

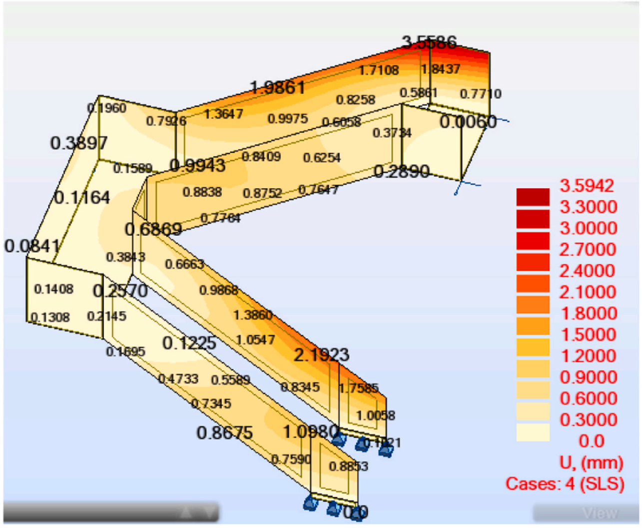

Fig. 14. Deflection in all the shell elements (handrails and landings) under SLS.

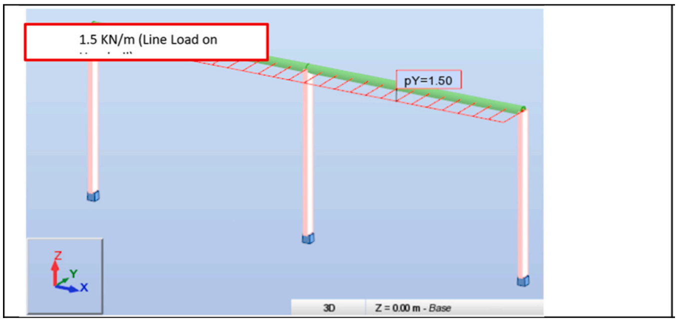

Fig. 15. Loading on the Handrail.

maintenance and early failure detection, particularly beneficial in high-risk installations like stadiums or high-rise buildings.

Advances in finite element modeling tools, such as LS-DYNA and RF-Glass, enable more accurate simulations of complex loading scenarios, including impact and fatigue. Sustainable material integration is also gaining traction, with bio-based interlayers, low-carbon glass production, and circular design principles becoming more prevalent. Additionally, additive manufacturing is enabling the creation of optimized metal brackets and modular balustrade systems that reduce material waste and installation time. As prescriptive codes evolve toward performance-based design, artificial intelligence and machine learning are being leveraged to optimize design parameters and predict failure modes, paving the way for safer, more efficient, and aesthetically advanced glass balustrade systems.

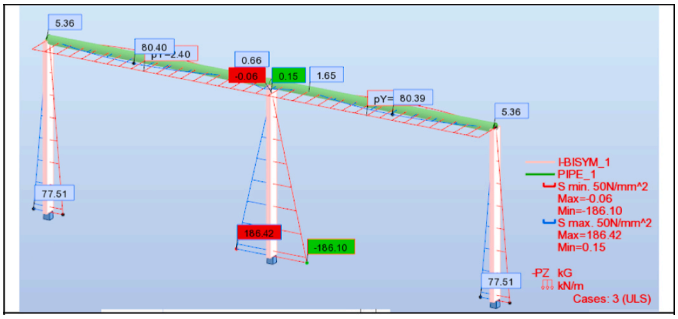

Fig. 16. Induced stress under ULS.

Emerging technologies such as self-healing interlayers (e.g., PVB with microcapsules) and digital twin simulations for real-time glass stress monitoring are reshaping balustrade design. These innovations address current gaps in long-term durability and in dynamic load testing under standards like EN 12600.

8. Conclusions

The structural design of glass balustrades demands a multidisciplinary, performance-based approach that harmonizes architectural vision, material behavior, regulatory compliance, and engineering rigor. This study has outlined a comprehensive framework for the design and validation of glass balustrade systems, grounded in international standards and substantiated by practical case studies.

The codes reviewed emphasize critical considerations, including occupancy-specific load criteria, height regulations, post-breakage safety, and anchorage integrity. The case studies further demonstrate that when laminated or toughened glass is paired with suitable interlayers, robust steel brackets, and ETA-certified anchors, it can reliably satisfy both strength and serviceability requirements.

Additionally, the comparative analysis of global standards and deflection criteria offers a valuable reference for designers seeking to implement best-practice methodologies. High-occupancy and wind-exposed applications, such as stadiums and podiums, particularly benefit from risk-informed design strategies, including built-in redundancy and post-failure containment features.

In conclusion, the structural reliability of glass balustrades is determined not solely by material properties but by a holistic systems approach that integrates code compliance, accurate structural modeling, and meticulous detailing. Future research should investigate the effects of dynamic loading, long-term durability under extreme environmental conditions, and the evolving contribution of laminated glass to sustainable and resilient building envelope design.

Practical Recommendations for Designers
Include:

- Always verify PFLS for frameless systems
- Consider the interlayer type in deflection checks
- Harmonize load combinations when working internationally
- Use mesh convergence in FEM

The holistic design approach must now balance code compliance

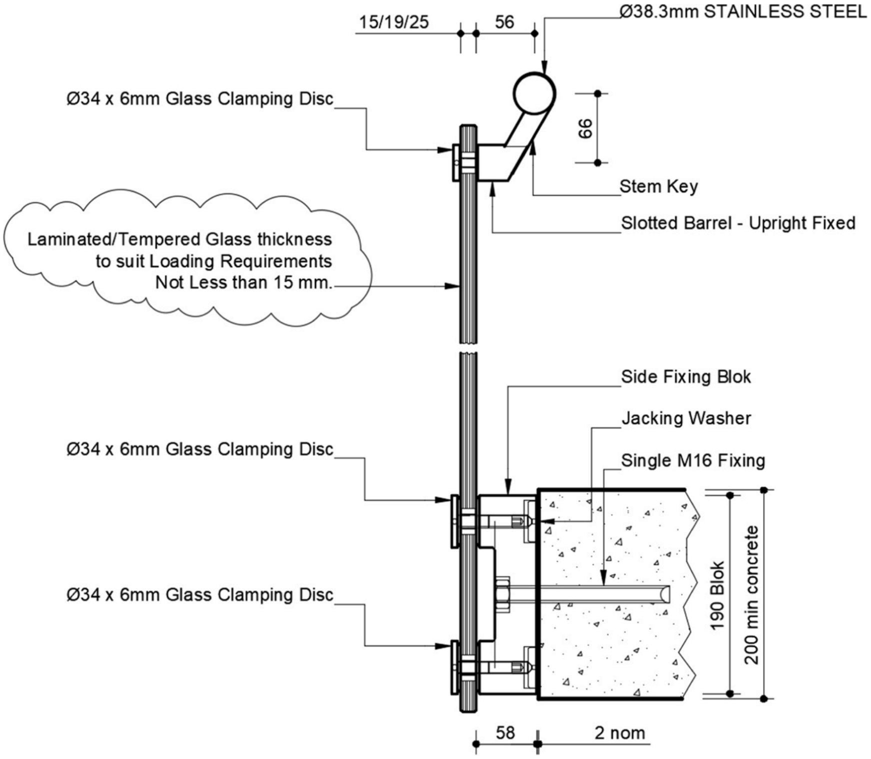

Fig. 17. Cross-sectional view of the handrail and glass.

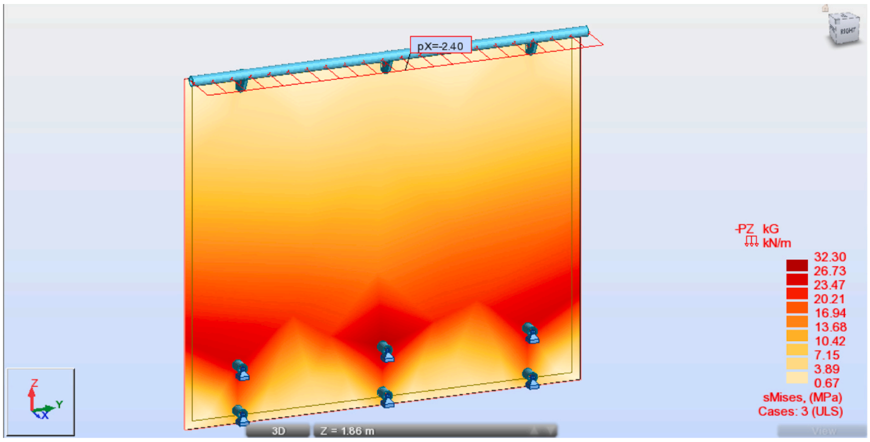

Fig. 18. Induced stress in glass under ULS (1.4DL + 1.6 LL).

with environmental targets (e.g., EN 15804) and risk mitigation, particularly for extreme environments. These findings provide a robust framework for the safe and efficient design of glass balustrades globally.

Nomenclature

Symbol	Meaning	Unit
fy	Yield strength of steel	MPa
fu	Ultimate tensile strength of steel	MPa
E	Modulus of elasticity	MPa
G	Shear modulus	MPa
μ	Poisson's ratio	-
α	Thermal expansion coefficient	/°C
γ	Unit weight	kN/m^3
DL	Dead Load	kN/m^2
LL	Live Load	kN/m^2
WL	Wind Load	Pa
ULS	Ultimate Limit State	-
SLS	Serviceability Limit State	-
D/C	Demand-to-Capacity ratio	-
PVB	Polyvinyl Butyral (interlayer)	-
SGP	SentryGlass Plus (ionoplast interlayer)	-
EVA	Ethylene-Vinyl Acetate (interlayer)	-
ETA	European Technical Assessment	-
FEM	Finite Element Modeling	-
CAD	Computer-Aided Design	-

CRediT authorship contribution statement

Antonio Formisano: Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Muhammad Tayyab Naqash:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Bedon:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization.

Authors' Contributions

MTN conceptualized the study, conducted structural analysis, and led the writing of the manuscript. CB provided technical insights on glass behavior, contributed to the comparative code analysis, and reviewed the case studies. AF supervised the structural design methodology, coordinated data interpretation, and assisted in refining the final draft.

Declaration of Generative AI and AI-assisted technologies in the writing process

Artificial intelligence tools (e.g., Grammarly and ChatGPT) were used to assist with grammar correction, language refinement, and clarity enhancement.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Antonio Formisano reports was provided by University of Naples Federico II. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data and materials used in this study are included within the manuscript.

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