Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.buildingmaterialsstructures.com

https://doi.org/10.5937/GRMK2600004T UDK: 692.23:624.078.4

Technical paper

Design and structural performance of connections in façade

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Article history

Received: 08 January 2026
Received in revised form:
19 February 2026
Accepted: 23 February 2026
Available online: 09 March 2026

Keywords

curtain walls,
steel brackets,
shear connectors,
thermal movement,
anchorages,
FEA,
deflection,
balustrade connections

ABSTRACT

This study investigates the structural performance and design considerations of various connection types used in curtain wall and balustrade systems. Emphasis is placed on horizontal-to-vertical and vertical-to-beam/floor connections, which are critical for transferring loads and maintaining façade integrity. The paper evaluates different connector configurations, ranging from shear-only to combined shear-moment. It examines the use of extruded steel brackets, including fin plates and shoe brackets, in detailed applications. Thermal loading is addressed through the incorporation of slotted holes and expansion provisions, ensuring serviceability under fluctuating temperature conditions. The study also explores the use of custom-fabricated brackets, kicker supports, and steel inserts in areas with spatial constraints.

Additionally, anchorage design is analyzed, with attention to edge distances, embedment depths, and concrete strength to prevent brittle failures, particularly in glass-supported systems. Finite Element Analysis (FEA) is used to validate connection performance under service and ultimate loading conditions. The findings offer practical insights for engineers and designers aiming to ensure robust, compliant, and efficient curtain wall connections.

1 Introduction

Curtain wall systems are prefabricated, non-load-bearing façade assemblies that serve as the outer envelope of modern buildings. While they do not carry primary structural loads, they play a vital role in protecting the building from environmental influences, facilitating daylighting, and contributing to architectural expression. Typically composed of glass, aluminum, and composite panels, curtain walls are engineered to integrate thermal insulation, air-tightness, and structural performance within a lightweight framework [1], [2]. These systems are designed to resist environmental loads such as wind, thermal variations, and impact while allowing for large glazed areas and lightweight façades. Although curtain walls do not carry the primary building loads, their structural integrity is highly dependent on the design and performance of their connection systems [3], [4], [5], [6].

The role of connections in curtain walls is critical. These elements facilitate load transfer between the façade and the primary structural frame, accommodate movement due to thermal expansion or building sway, and maintain system alignment and stiffness [7]. Poorly detailed connections can lead to serviceability issues, excessive deflection, or even brittle failure, particularly in systems involving glass. As a result, the design, fabrication, and performance of curtain wall connections have been the focus of extensive research and engineering practice. Multiple types of connectors are used in curtain wall systems, each with distinct mechanical behavior and application scope. Studies have compared shear-only, moment-resisting, and combined shear-moment connectors, evaluating their load-carrying capacity and deformation characteristics. The choice of connector significantly influences the overall performance of the façade system, affecting load paths, deflection limits, and stress concentrations [8].

The use of extruded brackets, including fin plates and shoe brackets, has been widely explored due to their structural efficiency and fabrication flexibility [9]. Thermal movements present another key design challenge in curtain wall connections. As the façade is exposed to diurnal and seasonal temperature fluctuations, thermal expansion and contraction must be accommodated without compromising connection integrity. To address this, slotted holes are commonly introduced to allow controlled movement, as discussed by Ting [10]. Proper sizing and positioning of these features are crucial to maintaining long-term serviceability, particularly amid increasing demands for story drift and seismic resilience in building design.

Special attention has also been given to vertical-to-beam or floor connections, particularly in single-span curtain walls that use pin connections. These configurations often struggle to meet deflection criteria, leading researchers to propose

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alternatives such as kicker brackets or steel inserts, especially in systems with depth or width limitations. Such solutions enhance performance while maintaining the architectural demands for minimal intrusion.

The anchorage system, which connects brackets or frames to the building structure, is another vital design component. Factors such as edge distance, embedment depth, concrete strength, anchor type, and spacing directly influence the pull-out resistance and load distribution of the system. Research [11] has shown that overlooking these parameters can lead to glass breakage or brittle failures, especially at fixing points near the panel edges. Recent research by Cuong et al. [10] demonstrated that anchor pull-out strength in thin UHPC panels is highly influenced by embedment depth and bottom diameter, with failure typically occurring through conical breakout patterns.

Curtain wall systems use different connectors, primarily categorized by their function in managing structural loads and accommodating building sway and thermal movements of structural members [11]. The primary types of curtain wall anchors include fixed anchors, slotted (movement-accommodating) anchors, F- and T-clips, embed anchors, and anchor channels, each designed to manage structural loads, accommodate building movement, and ensure precise installation (see Table 1). These embedded anchors play a vital role in transferring loads, such as dead weight, wind, and seismic forces, from the façade to the main structure, while also allowing necessary adjustments during installation and long-term serviceability [8].

Selecting the appropriate anchor type requires balancing structural capacity, movement accommodation, ease of installation, and architectural intent. Early coordination between façade engineers, structural designers, and installers is essential to ensure anchor systems are correctly integrated into the overall curtain wall design.

This paper builds on insights from prior studies and project applications to examine the design considerations, structural behaviour, and performance validation of various curtain wall and balustrade connection types. Particular emphasis is placed on the use of finite element analysis (FEA) to evaluate custom-fabricated brackets, wall-mounted supports, and parapet-mounted frame systems. By integrating analytical models, strength checks, and real-world case studies, the study aims to provide practical guidance for engineers and designers involved in façade connection design.

2 Literature review

The performance of curtain wall systems depends heavily on the design and detailing of their connections. Over the past two decades, numerous studies have focused on the structural behaviour, material selection, anchorage design, and thermal considerations of curtain wall connections. This section reviews the key findings from previous research, organized by connection type and design aspect.

2.1 Connector types and structural behavior

Studies have shown that the type of connector used in curtain wall systems, whether for shear, Moment, or combined shear-moment transfer, significantly impacts overall structural behaviour. Yin et al. [12] conducted a detailed investigation into the shear bearing capacity and mechanical behavior of Perfobond rib shear connectors (PBL shear connectors), revealing that their deformation modes, strain distributions, and force-transfer mechanisms significantly influence overall structural performance. Their findings emphasized that connector behavior under shear loading, including ductility and failure progression, plays a critical role in determining stress distribution and stiffness within the connected system.

Similarly, the classification of curtain wall connections as pinned, fixed, or semi-rigid affects the way loads are transferred between mullions, transoms, and the primary structure. Designers must select connectors that align with both the mechanical performance requirements and the architectural constraints of each project.

Table 1: Curtain Wall Anchor Types and Their Functions

Anchor Type	Key Function	Application Scope
Fixed Anchors (Dead Load Clips)	Provide rigid support to carry the weight (dead load) of the curtain wall down to the structure. Do not allow vertical movement.	Installed at base or intermediate floors to transfer vertical loads; requires precise alignment and installation.
Slotted Anchors (Movement-Accommodating)	Allow for vertical and in-plane movement due to thermal expansion, seismic activity, or building sway, while still resisting lateral loads.	Used the above fixed anchors in multi-story systems to accommodate movement and reduce stress concentrations. Ideal for dynamic buildings.
F-Clips and T-Clips	Simple slide-in connectors for quickly attaching mullions to transoms or perimeter frames. F-clips are for jambs; T-clips for intermediates.	Common in stick-built systems for efficient, onsite installation and alignment of vertical framing members.
Embedded Anchors	Cast into concrete during construction to serve as precise, pre-positioned connection points for curtain wall brackets.	Used in slab or beam edges to ensure anchor accuracy from the outset; critical for tolerance control in high-rise and complex installations.
Anchor Channels	Embedded channels that accept adjustable T-bolts for onsite alignment flexibility. Enable fine-tuning of anchor positions.	Ideal for modern curtain walls requiring adjustability, tolerance management, and simplified installation.
Point-Supported Spider Fittings	Directly support glass panels without framing, transferring loads to the primary structure with minimal visual obstruction.	Used in high-transparency, frameless glazing applications such as atriums, lobbies, and architectural feature walls.

2.2 Bracket types and fabrication methods

The use of extruded aluminium brackets is a common practice in both aerospace and building applications due to their lightweight and adaptable structural performance. Na et al. [13] used T-shaped hinge brackets to overcome the limitations of conventional bending or welding methods, which often compromise durability under operational loads. Their approach enabled the mass production of geometrically precise brackets while significantly reducing manufacturing costs. In a related context, Ambroziak et al. [9] studied curtain wall systems. Their study demonstrated that the structural performance of EN AW-6060 T66 aluminium brackets can be significantly improved by adding cover plates (straps), resulting in a 50% reduction in displacement and stress concentrations under load. Finite element simulations confirmed the effectiveness of such reinforcement, showing a shift from plastic to elastic behavior in critical regions.

Complementing these findings, Park investigated the use of carbon fiber/epoxy composite materials in curved aerospace brackets, applying classical laminate theory and FEA [14]. The study confirmed the high structural integrity and buckling resistance of composite brackets under multi-axial loads. Collectively, these studies emphasize the critical roles of material selection, manufacturing technique, and reinforcement strategy in optimizing bracket performance under both static and dynamic loading conditions. In parallel with advancements in bracket design and fabrication, contemporary research also emphasizes integrating structural systems with sustainability-oriented façade technologies. Fernando et al. [17] provide a comprehensive review of modern façade systems, including double-skin, adaptive, and PV-integrated façades, highlighting their energy efficiency and design complexities. The application of robust, adaptable connection systems becomes even more critical as these façade types demand more dynamic, responsive structural interfaces.

The study also highlighted the benefits of prefabricated bracket assemblies, which can improve installation speed and dimensional accuracy while reducing onsite welding and alignment issues.

2.3 Thermal effects and accommodation

Thermal expansion and contraction of façade components present a constant challenge in curtain wall design. Improper detailing can lead to constraint-induced stresses, particularly around rigid connections. Curtain walls designed for extreme environments, such as desert climates, must accommodate significant thermal expansion due to large daily and seasonal temperature fluctuations. To address this, systems incorporate slotted anchors, expansion joints, and sliding connections that enable controlled movement of aluminum components without overstressing glass seals or structural fixings. Flexible gaskets and silicone joints with high cyclic performance absorb differential movement while preserving weather-tightness.

Additionally, isolating curtain wall anchors from slab edges prevents the transfer of building movement into the façade. Thermal modeling during the design phase ensures that sightlines, gasket compression, and drainage systems perform effectively across the temperature range, thereby safeguarding long-term façade integrity and appearance [15]. Incorporating thermal allowances into the connection detailing is now considered best practice, particularly for horizontal-to-vertical joints and vertical-to-floor anchors, where differential movement is most pronounced.

2.4 Vertical-to-floor/beam connections and serviceability

Serviceability issues, such as excessive deflection, are common in single-span fixed curtain walls where structural continuity is interrupted. As highlighted by Wagner [19], traditional span-based deflection limits often fail to adequately address the performance needs of building enclosures, particularly when supporting elements such as curtain walls are subjected to accumulated vertical movements between floors. In such cases, the use of additional support strategies, such as vertical movement joints and coordinated deflection tolerances, is essential to mitigate serviceability issues and ensure proper alignment and stability of the enclosure system.

Where depth or width constraints limit the use of traditional brackets, researchers have proposed steel inserts to meet serviceability and strength criteria. Formisano and Naqash. [16] explored the application of such inserts in compact curtain wall assemblies and found that they significantly improve load transfer and anchorage behavior without increasing the visual footprint.

2.5 Anchorage Design Parameters

The connection between curtain wall brackets and the primary structure typically relies on chemical or mechanical anchors, or cast-in anchor channels. Several key parameters, including concrete compressive strength, edge distance, embedment depth, anchor spacing, and steel-to-concrete interface behavior, govern their performance. Ciascaiu et al. [17] conducted a detailed numerical and analytical evaluation of cast-in anchor channels used in curtain wall façades. They demonstrated that shallow embedment or insufficient spacing can significantly increase the risk of concrete cone failure, especially near slab edges. Their study highlighted that modifying the anchor head geometry, such as incorporating welded reinforcement plates, can enhance anchorage performance by increasing the effective breakout cone and delaying brittle failure mechanisms in the concrete substrate.

Their research stressed the importance of following manufacturer guidelines and code provisions to ensure anchors can safely resist both pull-out and shear forces. In practical applications, inadequate anchorage remains one of the most common sources of failure in poorly detailed curtain wall systems. The literature provides a strong foundation for understanding the structural behaviour and design challenges of curtain wall connections. From connector type selection and thermal accommodation to anchorage detailing and fabrication methods, each aspect plays a critical role in ensuring performance under service and ultimate loads. The current study builds on these findings by examining typical connection types through FEA simulations and case-based evaluations, offering practical guidance for engineers and façade designers.

3 Finite element analysis and typical curtain wall connections

3.1 Horizontal-to-vertical

Horizontal-to-vertical connections in curtain wall systems refer to the interface between transoms (horizontal members) and mullions (vertical members). These connectors are critical for transferring loads such as wind pressure and self-weight between framing members. Depending on the structural design requirements, these connections may transfer shear forces alone or both shear forces and bending moments. The selection of connector type (e.g., pinned, fixed, or semi-rigid) often depends on the expected load path, deflection limits, and the need for thermal movement accommodation. Extruded aluminum or fabricated steel brackets are commonly used, offering structural efficiency and ease of installation. In many cases, slotted holes are incorporated to allow for thermal expansion and contraction of the framing members, ensuring long-term serviceability of the façade system.

Extruded brackets are commonly used in the fabrication of connectors, particularly in steel. These brackets offer enhanced strength and versatility in connecting the transoms and mullions. The use of extruded brackets allows for efficient load transfer while maintaining structural stability.

Thermal loading is an essential consideration in curtain wall design. The framing members, especially the verticals, need to accommodate thermal expansion and contraction. Slotted holes are often incorporated into the design to provide ventilation and allow framing members to move during temperature fluctuations. The size and distribution of the slotted holes are determined based on structural calculations and thermal loading requirements.

Field investigations have shown that improper or missing frame seals at mullion intersections and splice joints are a leading cause of water infiltration in curtain wall systems. As McCowan and Kivela [18] observed, even minor deficiencies, such as omitting a quarter-ounce of silicone sealant, can result in widespread leakage, requiring full reglazing and costly rework. Ensuring compliance with manufacturer installation instructions and implementing rigorous quality control during construction are critical to achieving long-term performance.

As curtain wall configurations vary significantly from project to project, it is often infeasible to adopt standardized bracket designs. Instead, brackets are typically custom-fabricated and require verification through manual or numerical calculations. Therefore, when brackets are usually fabricated per site conditions, they need to be checked. Usually, manual calculations are performed to verify thicknesses and the required number of bolts or anchors. Nevertheless, the client/consultant may require more detailed checks, depending on the sensitivity of the case. For example, in this section, we are highlighting a case where a mullion is connected to a bracket that is connected to a floor. Eq (1) is used to o check the plate connection under shear:

$$\tau = \frac{V}{A_s} \tag{1}$$

where τ is the shear stress in brackets (MPa), A_s is the shear area of the bracket (mm²), and V is the spplied shear force (N).

The induced shear stress in the connector plate is evaluated using Equation (1), ensuring it remains below the material yield limit. Bending stress in the Horizontal Bracket Plate is calculated using Eq. (2), which is critical for plate thickness design.

$$\sigma = \frac{M \cdot y}{I} \tag{2}$$

where σ is the bending stress (MPa), y is the distance from neutral axis (mm), and M is the bending moment applied (N·mm) / Moment at base of post (kNm).

The design of horizontal-to-vertical connections in curtain wall systems follows a structured engineering workflow that ensures both structural adequacy and constructability. The flowchart in Figure 1 outlines the key steps involved in evaluating such connections. The process begins with identifying the structural configuration and selecting an appropriate connector type, whether pinned, fixed, or semi-rigid, based on the intended load path and movement constraints.

Relevant load cases, including dead load, wind pressure, thermal effects, and possible impact forces, are then applied. Structural checks are carried out to verify plate stresses, bolt tension, shear capacity, and thermal movement accommodation. Particular attention is paid to edge distances and anchor spacing, which are critical for ensuring proper load transfer and avoiding brittle failure in the surrounding concrete.

The final verification may be performed using hand calculations or Finite Element Analysis (FEA), especially where complex geometries or high loads are involved. Upon satisfying both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) criteria, the design is validated for use in the curtain wall system.

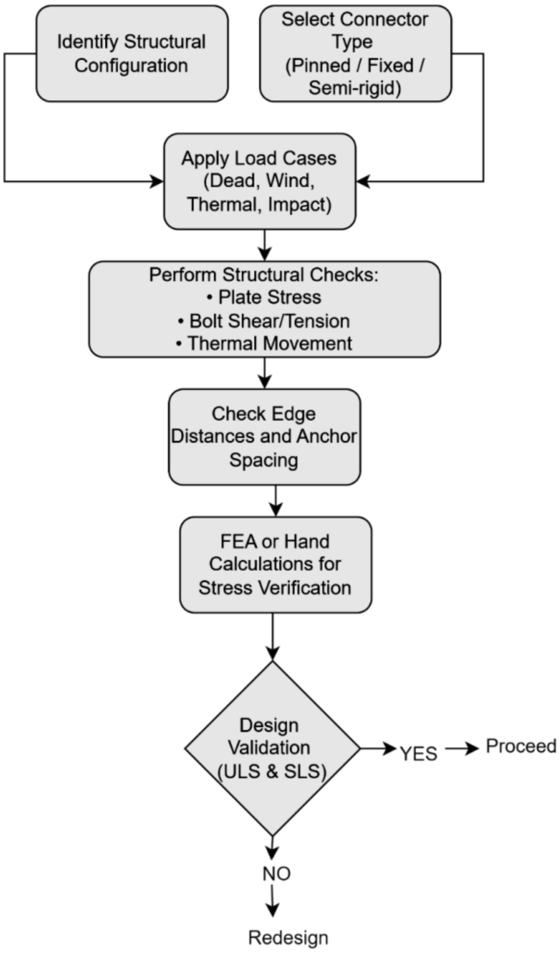

Figure 1. Connection design procedure for curtain wall brackets

As part of this study, two custom-fabricated steel bracket configurations were evaluated at a typical horizontal-to-vertical façade connection between mullions and transoms. The objective was to verify bracket strength and anchor demand under governing service and ultimate load combinations using finite element analysis (FEA).

1) Brackets analyzed (geometry and material)
Two bracket types were considered:
- Bracket Type 1 – Plate bracket (unstiffened)
    - Fabricated from mild steel / S275 plate.
    - Primary plate thickness: 12 mm (as modelled).
    - Connection consists of a base plate (fixed to the supporting structure) and bracket legs connecting to the mullion/transom interface (as shown in Fig. 2a).
- Bracket Type 2 – Stiffened bracket
    - Same base concept but incorporating stiffener plates to increase out-of-plane rigidity and reduce local bending at the junction (Fig. 3a–3b).
    - Material: S275 steel (yield strength $f_y \approx 275$ MPa).

2) Fasteners/anchors (bolts, type, and demand reporting)
- The bracket-to-support connection is provided via chemical anchors.
- Anchor size assessed: M12 chemical anchors (12 mm nominal diameter), bonded using epoxy/resin adhesive systems (e.g., Hilti HIT-RE 500 or equivalent).
- Anchor force extraction was performed from the FEA reaction outputs at each anchor location (Fig. 2b):
    - Top anchors: shear components of 13.32 kN and 5.28 kN in orthogonal directions (resultant shear ≈ 14.3 kN) and axial tension of 0.23 kN.
- Based on the above demands, M12 chemical anchors are adequate for the connection for the analysed load cases (subject to final verification against the selected manufacturer's ETA/ICC data for the actual embedment, spacing, edge distances, concrete grade, and installation conditions).

3) Loads and load combinations considered
The brackets were evaluated under representative façade actions, including:
- Self-weight (dead load) of bracket/connected components (as applicable in the model).
- Wind load is transferred through the mullion–transom connection to the bracket.
- Thermal effects (temperature-induced movements/forces) are included in the load cases/combination.
- Results were checked for both:
    - Serviceability load level (for operational performance), and
    - Ultimate load level (for strength verification).

4) FEA software and modelling approach (brief but audit-friendly)
- Analysis method: Finite Element Analysis (FEA) with 3D solid/shell representation of the bracket components and bolt/anchor constraints.
- Output checks:
    - von Mises stress distribution in bracket plates and stiffeners.
    - Support/anchor reactions resolved into shear components and axial tension per anchor.
- Acceptance criteria:
    - Peak stresses compared against S275 yield strength (275 MPa) for strength adequacy.
    - Anchor forces compared to anchor capacity (manufacturer/design standard checks) to confirm adequacy.

5) Key results and conclusions
- Type 1 (unstiffened bracket):
    - Maximum von Mises stress in the 12 mm plate: 63.15 MPa (Figure 2a).
    - This is well below 275 MPa, indicating acceptable stress levels.
    - Anchor demand (top bolts): resultant shear ≈ 14.3 kN, axial tension 0.23 kN (Figure 2b).
    - M12 chemical anchors are adequate for the extracted forces.
- Type 2 (stiffened bracket):
    - Maximum von Mises stress: 234 MPa (Figure 3b).
    - This remains below 275 MPa, confirming the stiffened bracket is also structurally adequate under the applied service and ultimate loads.

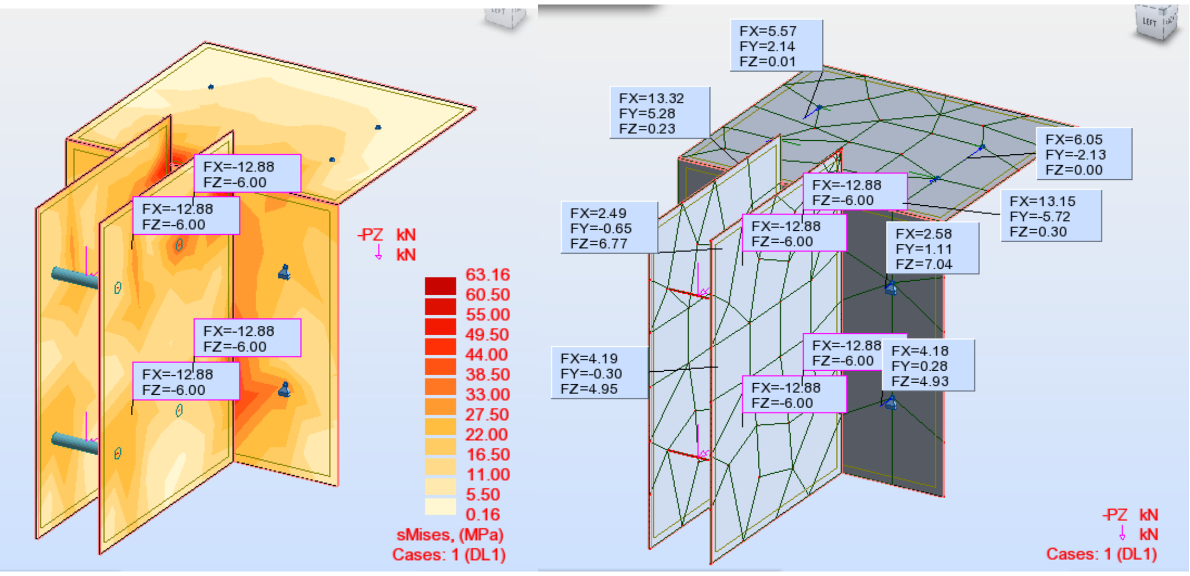

Figure 2. (a) Stresses and (b) reactions induced on individual anchors in the Type 1 bracket

Overall, both bracket configurations meet the strength criteria for the analysed loading, and the anchor reactions extracted from the model indicate that M12 chemical anchors are suitable for the connection, provided final detailing (embedment, spacing, edge distance, and substrate properties) aligns with the anchor design approval data.

3.2 Wall/column-mounted connections

Wall- or column-mounted brackets are critical components in curtain wall systems, particularly when vertical mullions or structural elements must be anchored directly to the building's primary structure, such as a reinforced concrete wall or column, rather than to floor slabs. These connections provide structural support, resist lateral loads, and contribute to the overall stability of the façade system.

The wall-mounted curtain wall connection system, as illustrated in Figure 4, utilises a custom-fabricated 12 mm-thick steel bracket that projects perpendicularly from the structural wall surface. This bracket includes a sloped arm at approximately 130° that connects to a Q01B-20 Kinlong tension rod. The bracket serves as the primary load-bearing element, transferring the weight of the mullion or glass assembly to the structural substrate through anchor bolts. The integrated tension rod plays a key role in resisting pull-out forces and in stabilising the bracket under lateral loads, such as wind or seismic actions. By introducing a triangulated load path, the tension rod reduces rotation and bending moments in the bracket, enhancing the overall stability of the system. It is bolted through the bracket, allowing for onsite adjustments during installation. The bracket is anchored to the concrete wall using HST M16 anchor bolts arranged vertically, with edge distances and spacing (typically 25 mm to 35 mm from edges and 150 mm to 250 mm apart) designed to comply with anchorage standards and ensure adequate breakout strength. The external Dryvit EIFS (Exterior Insulation and Finish System) is applied beyond the structural bracket zone, requiring coordination between façade engineers and cladding contractors to maintain thermal continuity and aesthetic alignment. Geometrically, the bracket extends 175 mm from the wall, with a clear rod length of 163 mm, suitable for accommodating external cladding while minimizing eccentricity. This configuration is specifically designed to transfer vertical dead loads to the structure, resist out-of-plane lateral loads, and allow modular installation with minimal deflection and rotation at the connection point. Proper attention must be paid to anchor spacing, bracket material grade, and interface coordination with finishes to ensure structural integrity and serviceability. The system offers several advantages, including design flexibility to accommodate various wall offsets, efficient load transfer via tension rods, suitability for retrofit or non-slab-mounted curtain walls, and ease of installation with bolted components and minimal onsite welding.

Wall- and column-mounted connections, such as the one shown in Figure 4, are essential for projects where curtain wall elements cannot be slab-mounted. The combination of fabricated steel brackets, tension rods, and mechanical anchors provides a robust solution that balances structural performance with installation flexibility. These connections should be carefully engineered, especially with respect to anchorage design and alignment with architectural finishes.

Figure 4 shows a 12 mm-thick fabricated steel bracket anchored with HST M16 bolts and reinforced with a Q01B-20 Kinlong tension rod for lateral stability and load transfer.

3.3 Vertical-to-beam/floor connections

The vertical members of the curtain wall system are connected to the beams or floors using wall-mounted brackets or shoe brackets, depending on the height of intermediate supports. These brackets, similar to the connectors, can also be extruded for increased strength and durability. Steel fabrication is commonly employed for these brackets to withstand the loads and forces imposed on the connections.

Challenges arise in single-span curtain walls with pin connections at the ends. The serviceability limit state often governs the structural design in such cases, posing challenges in meeting deflection limits. Designers may opt to use kicker brackets below the top connections, especially when false ceilings are present. However, restrictions on the provision of kicker brackets necessitate alternative solutions.

Designers often employ steel inserts to address limitations in depth and width. These inserts help satisfy the required limit states within the curtain wall system's restricted dimensions. Careful consideration of the design and installation of these steel inserts is crucial to ensure optimal structural performance. For kicker-supported or pin-supported mullions, the deflection check is carried out using Eq (3).

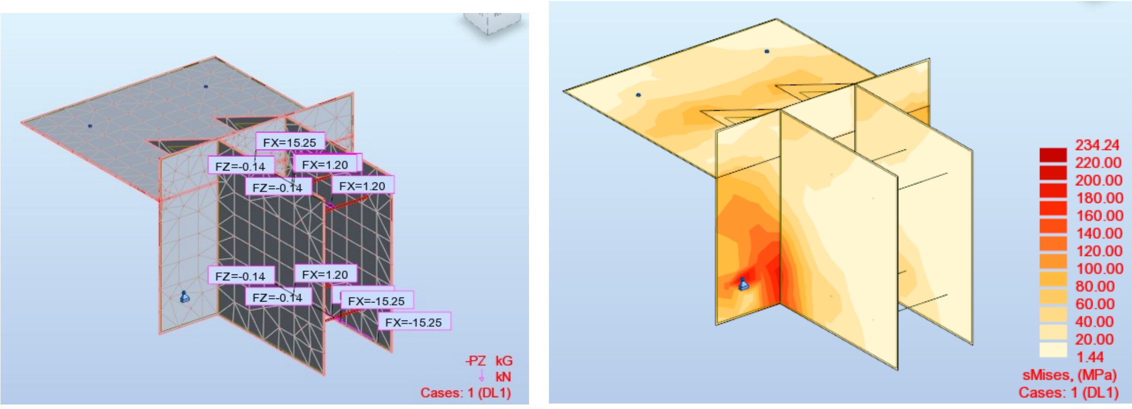

Figure 3. (a) Numerical model with the loading and (b) stresses in the Type 2 bracket

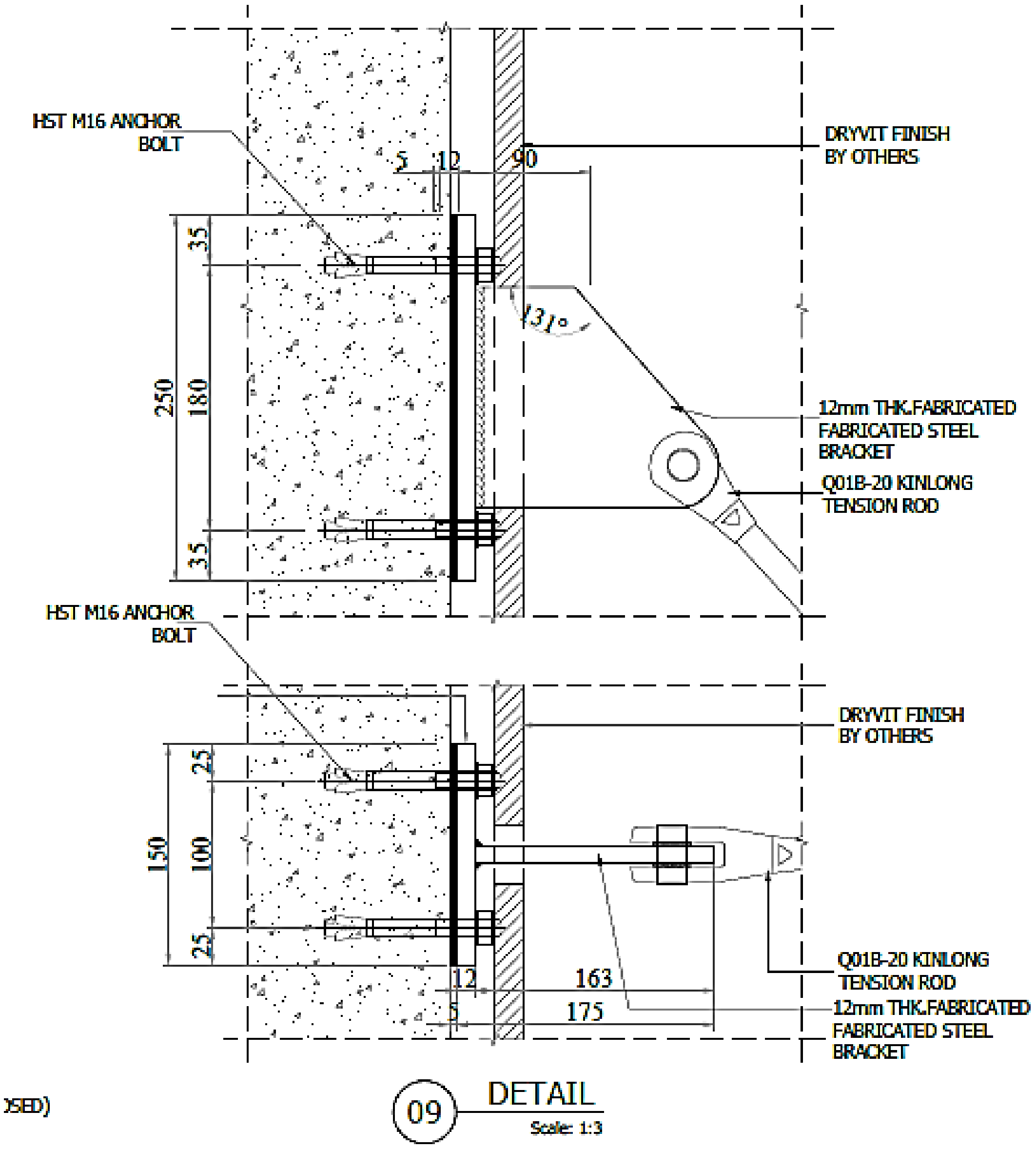

Figure 4. Technical detail of wall/column-mounted curtain wall connection

$$\delta = \frac{5wL^4}{384EI} \tag{3}$$

Where, *δ* is the maximum vertical deflection (mm), w is the uniform load (kN/m), *L* is the span length (mm), *E* is the Young's modulus of elasticity (MPa), and *I* is the moment of inertia of bracket section (mm⁴).

Compare δ to the allowable deflection limit (e.g. $\delta_{limit} = \frac{L}{250}$).

The European Façade Product (EFP) 50 Façade System offers a range of shoe brackets widely used for vertical-to-floor connections due to their standardized dimensions, high load capacity, and ease of installation (see Figure 5). Two commonly referenced models are:

- EFP 13700 – Dimensions: 170 mm × 85 mm
- EFP 13740 – Dimensions: 205 mm × 100 mm

These brackets are typically extruded aluminum or fabricated steel components designed to support vertical mullions by anchoring them directly to the building structure. The geometry of these brackets allows for:

- Efficient load transfer from the curtain wall mullions to the concrete or steel floor slab.
- Ease of alignment and onsite installation due to pre-drilled holes and adjustable slots.
- Thermal movement accommodation is mainly used in conjunction with slotted holes and elastomeric pads.

The shoe bracket design provides torsional and shear stability. When paired with chemical or mechanical anchors, it can be engineered to meet both the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) design requirements. The incorporation of drawings in the design documentation helps confirm clearances, edge distances, and bolt patterns, which are essential for compliance with structural and fire safety codes.

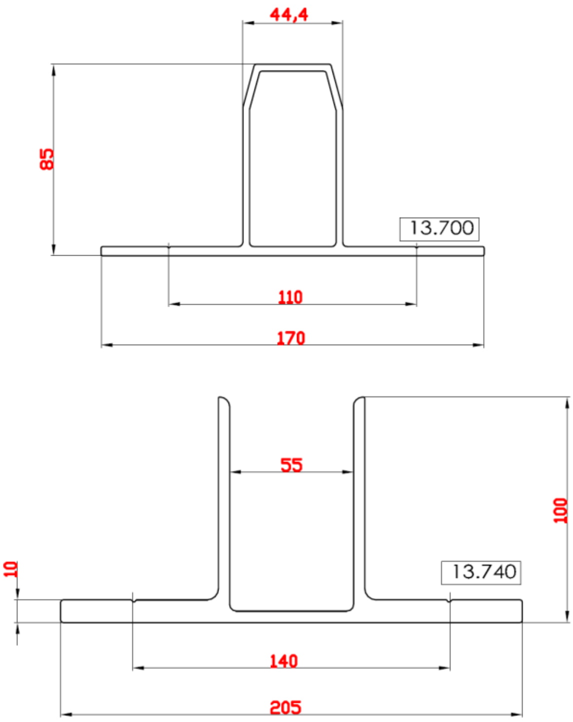

Figure 5. European Façade Product (EFP) 50 Façade System shoe brackets catalogue drawings (top) 13700 with size 170 × 85 and (bottom) 13740 with size 205 × 100

Typical shoe brackets used in vertical-to-floor curtain wall connections are shown in Figure 6 and Figure 7. These fabricated brackets are designed to support vertical mullions while allowing for efficient load transfer and alignment with structural elements. The bracket includes vertical plates for fixing, a central threaded rod for adjustability, and a base plate that accommodates anchor bolts. Such configurations are often used in systems with limited space or where modular installation is preferred.

Thermal loading is a crucial consideration in curtain wall design, and several studies have addressed this aspect. Naqash et al. [5] investigated the effects of thermal expansion and contraction on curtain wall connections and proposed the use of slotted holes to accommodate framing member movement. They highlighted the importance of proper sizing and distribution of slotted holes to ensure the structural integrity of the system under thermal loading.

3.4 Parapet-mounted steel frame connections

Parapet-mounted connections are a standard solution for installing auxiliary framing systems above roof parapets, especially when supporting secondary façade elements such as fins, shading devices, or aluminium cladding. These connections are typically designed to resist both vertical and lateral loads, including wind and dead loads from the supported elements.

The detail shown in Figure 8 represents a parapet-top connection involving a fabricated steel frame composed of rectangular hollow section (RHS) members. The main vertical frame (e.g., 120×60×5 mm steel tube) is anchored to

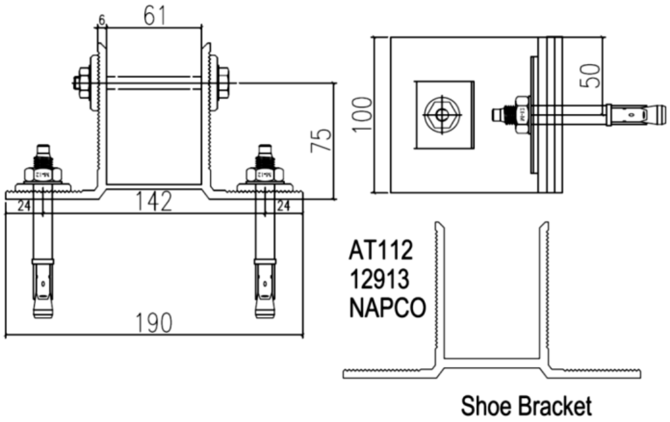

Figure 6. Technical drawing of a fabricated aluminum shoe bracket showing dimensions and bolt arrangement for mullion support

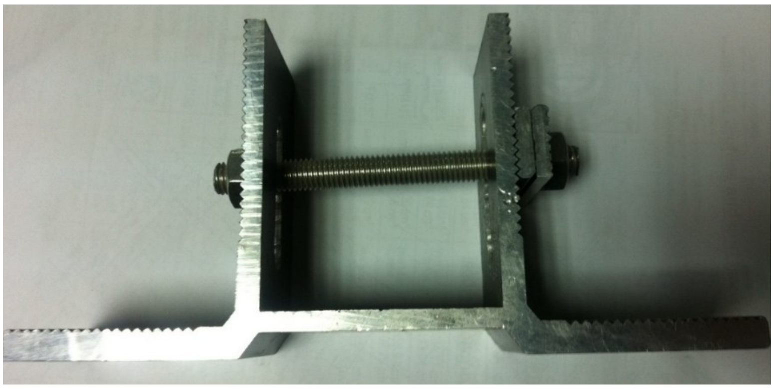

Figure 7. Photograph of the fabricated shoe bracket assembly with threaded rod and side fixing plates

the top of a reinforced concrete parapet using a steel base plate (300×100×10 mm) secured by M12 mechanical anchor bolts. The base plate is welded to the vertical steel tube on three sides, ensuring a rigid moment connection. In addition, a horizontal steel tube (50×50×4 mm) acts as a secondary framing element, providing lateral support and alignment for the aluminum cladding or screen system.

The mechanical anchors are placed at sufficient distances from the edge of the parapet (minimum 100 mm), and the parapet itself is assumed to be solid concrete with a minimum width of 200 mm, as validated in the structural calculations. The detail also includes provisions for 5 mm-thick SHS packing plates to level the top surface and accommodate tolerance adjustments during installation. The use of silicone sealing and aluminum flashing (as shown in the upper cladding zone) ensures watertightness and an architectural finish.

From the structural calculation report, the design checks confirm the adequacy of:

- The 10 mm thick base plate with dual M12 chemical anchors for the top fixing (tension = 22.01 kN, shear = 4.84 kN),
- The 6 mm side bracket with M10 stud bolts (shear = 24.37 kN, tension = 0.52 kN),
- The 5 mm fillet welds around the steel angle are sufficient to resist combined stress from dead and wind loads (total weld stress = 15.1 MPa < 220 MPa allowable).

This configuration ensures a robust, serviceable connection that transfers vertical and horizontal forces from the steel frame to the concrete parapet without compromising structural integrity. It is especially suitable for cases where the façade support needs to extend above the roof line or where slab anchorage is not feasible. Proper coordination with existing waterproofing, insulation, and finishes is essential to avoid thermal bridges and ensure long-term performance.

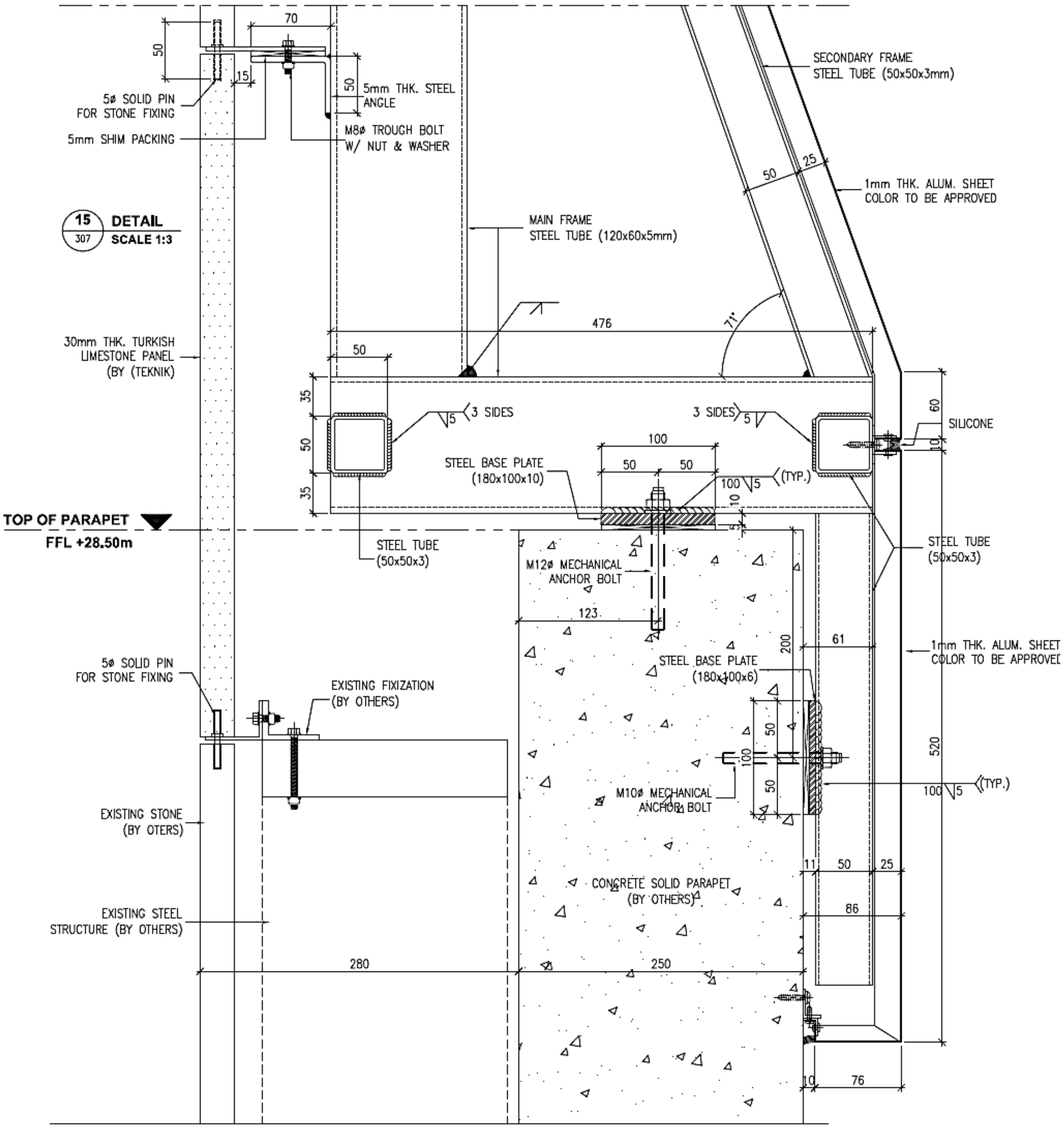

Figure 8. Technical details of parapet-mounted steel frame connection

Figure 8 shows steel tube framing, a 10 mm base plate, and M12 mechanical anchor bolts installed on top of a concrete parapet. The detail shown in Figure 9 represents a parapet-mounted bracket connection used to support a secondary steel frame above the building parapet. The connection consists of a rectangular steel tube welded to a 10 mm thick base plate, which is mechanically anchored to the concrete parapet using M12 anchor bolts. Designed to transfer both vertical loads and lateral wind forces, this connection plays a critical role in maintaining the structural stability of the attached façade system. A detailed analysis of this bracket is conducted to evaluate stresses in the plate, anchors, and welds under ultimate loading conditions, ensuring compliance with structural safety requirements.

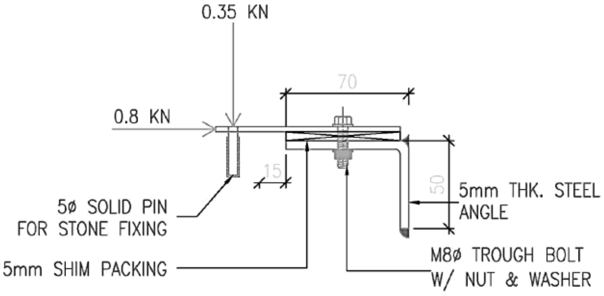

Figure 9. Technical details of stone cladding fixing bracket

Figure 9 shows a 5 mm-thick steel angle secured with an M8 through bolt, supporting a 5 mm shim packing and a 5 mm-diameter solid pin for stone anchorage. The bracket is designed to resist a vertical load of 0.35 kN and a horizontal wind load of 0.8 kN. To verify the structural adequacy of the parapet-mounted bracket connection, a finite-element model of the bracket was developed and analyzed under ultimate limit-state (ULS) loading conditions. The bracket was subjected to a factored vertical dead load of 0.35 kN and a horizontal wind load of 0.80 kN, as shown in the applied load case (refer to Figure 10). The meshing of the plates enabled accurate stress analysis across the bracket surfaces and bolt locations. Results indicate that the maximum von Mises stress in the plate is 218 MPa, well below the allowable limit of 275 MPa for structural steel (Grade 43), confirming the bracket's adequacy. Additionally, the stress in the M8 stainless steel bolts was found to be 12.51 MPa, which is significantly lower than the permissible bolt stress derived from material standards, ensuring safe performance under design loads. Further analysis of welds and anchor performance is included in the subsequent sections.

The top-left image shows the 3D model of the bracket, while the top-right illustrates the meshing and applied ULS loads (*Fx* = 0.80 kN, *Fz* = 0.35 kN). The bottom-left image shows the von Mises stress distribution in the bracket, with a maximum stress of 218 MPa, which is within the allowable limits. The bottom-right image shows the stress values for the M8 stainless steel bolts, with each bolt exhibiting a maximum stress of 12.51 MPa, confirming structural adequacy under the given loading conditions.

4 Design considerations for anchorages

Anchorages are vital components in curtain wall systems, providing stability and load transfer to the building structure. Several factors should be considered when designing anchorages. Edge distances, concrete strength, anchor types, and spacing play crucial roles in maintaining the integrity of the connections.

Ignoring any of these factors can lead to disastrous consequences, particularly due to the brittle failure of glass components commonly used in curtain walls. It is essential to carefully evaluate and address these design parameters to prevent potential failures and ensure the long-term performance of the curtain wall system.

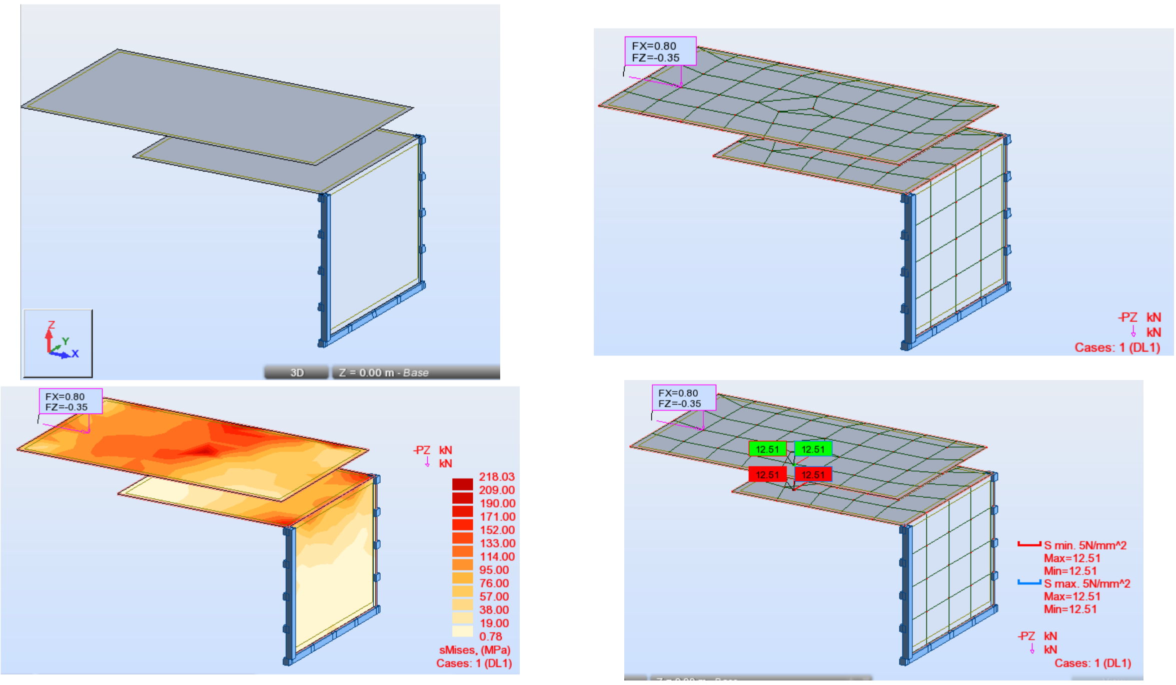

Figure 10. Finite Element Analysis (FEA) of the parapet-mounted bracket connection

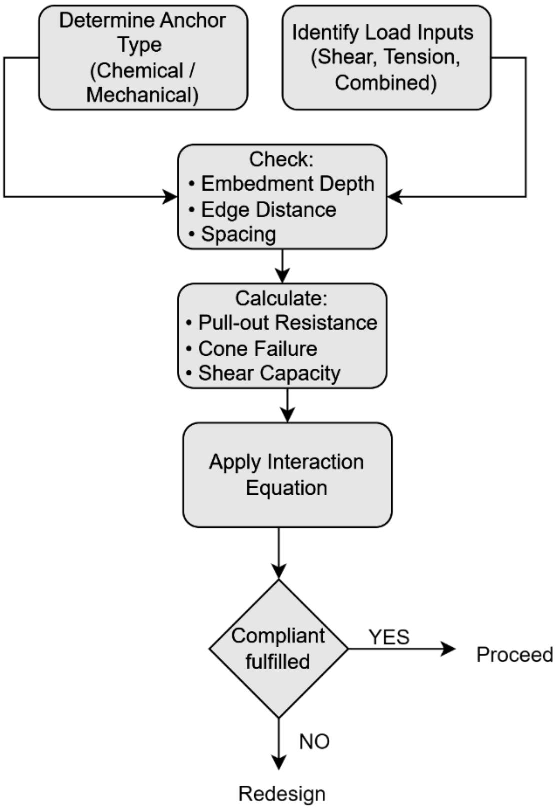

Figure 11. Anchor design workflow for curtain wall systems

The anchorage design process in curtain wall systems must ensure structural safety under combined shear and tension loads. Figure 11 illustrates a step-by-step methodology for evaluating anchor performance in accordance with Eurocode (EC2) [19], which includes type selection, load identification, embedment and edge checks, and final verification using interaction criteria. The process begins by selecting the appropriate anchor type, either chemical or mechanical, based on site conditions and loading requirements. Subsequent steps include identifying the applied loads (shear, tension, or combined) and verifying embedment depth, edge distances, and anchor spacing. Following these checks, the anchor's pull-out resistance, concrete cone failure, and shear capacity are calculated. These values are then assessed using the interaction equation, which ensures that the combined effects of applied forces remain within permissible limits. If compliance is achieved, the anchorage design is deemed structurally adequate. The Pull-Out Resistance of Anchor (Eurocode EC2) is given by Eq. (4).

$$N_{Rd} = \frac{\mathrm{k2} \cdot \mathrm{Ah} \cdot \mathrm{fck}}{\gamma_{Mc}} \tag{4}$$

Where, N_{Rd} is the anchor design resistance in shear and tension (N), k_2 is the coefficient depending on concrete condition (7.5 for cracked, 10.5 for non-cracked concrete), A_h is the bearing area of head of anchor (mm²), f_{ck} is the characteristic concrete compressive cylinder strength (MPa), and γ_M is the partial safety factor (typically 1.5).

Leading manufacturers offer standardized, code-compliant anchorage systems, along with proprietary software for accurate design and verification. Commonly used anchor systems in curtain wall applications include:

- Hilti [20]:
    - *Anchor Systems*: HST, HIT-RE 500 V3, HUS3
    - *Software*: Hilti PROFIS Engineering Suite
        - Allows EC2 and ACI-based anchor design, including interaction checks, breakout analysis, and 3D modeling.
- Fischer[21] :
    - *Anchor Systems*: FIS V Plus, FAZ II, FBN II
    - *Software*: Fischer FiXperience Suite
        - Offers module-based anchor design, concrete edge checks, and BIM integration.
- Mungo Fasteners [22]:
    - *Anchor Systems*: CM15, MT-Plus Resin Anchors
    - *Software*: Mungo Anchor Design Tool
        - Enables anchor selection and safety checks for façade brackets in accordance with Eurocode and local standards.

In modern curtain wall systems, anchoring system specifications are critical not only for structural safety but also for ensuring compatibility with construction tolerances, differential movement, and long-term durability. Several internationally recognized manufacturers offer certified chemical and mechanical anchors tailored for façade applications. These systems are backed by proprietary or third-party software tools that support code-compliant design in accordance with Eurocode (EN 1992-4) and ACI 318, simplifying the verification of load resistance, breakout strength, and interaction under combined shear and tension. These software tools assist designers and engineers in:

- Verifying pull-out and shear resistance under different load cases,
- Applying interaction equations for combined loading per EC2 or ACI,
- Ensuring concrete breakout checks at proper edge distances and embedment depths,
- Generating design reports with calculations, safety factors, and 2D/3D visualizations,
- Integrating with BIM workflows for clash detection and coordination.

This study primarily focuses on three widely used anchoring systems: Hilti, Fischer, and Mango Fasteners, each of which provides integrated software environments for anchor selection, performance assessment, and compliance documentation. However, to provide a broader industry perspective, Table 2 summarizes other commercially available anchoring systems and their corresponding software platforms.

By incorporating these advanced anchoring systems and leveraging their design software, façade engineers can achieve greater precision, safety, and installation efficiency, especially in projects with complex geometries or high-performance façade requirements.

Table 2: Common Commercial Anchoring Systems and Software Platforms

Manufacturer	Anchor Types	Software Tool	Code Compliance
Hilti [20], [23]	HIT-RE 500 V3 (resin), HST, HUS3	PROFIS Engineering Suite	EN 1992-4, ACI 318
Fischer [21]	FIS V Plus, FAZ II, FBN II	FiXperience Suite	EN 1992-4, ACI 318
Mungo [22]	CM15, MT-Plus Resin Anchors	Mungo Anchor Design Tool	EN 1992-4
Rawlplug [24]	R-KEX II, R-HPTII	EasyFix	EN 1992-4
Simpson Strong-Tie [25]	SET-3G, Titen HD	Anchor Designer™	ACI 318, ETAG, EN 1992-4
Würth [26]	W-VD, W-FAZ	Würth Anchor Design Tool	EN 1992-4
HALFEN (Leviat) [27]	HTA Cast-in Channels, HZA Anchors	HALFEN HTA Software	EN 1992-4
Spit / ITW [28]	Epcon C8, Tapcon	Spit DesignFix	EN 1992-4

5 Conclusions

The structural performance of curtain wall systems is intrinsically linked to the design and detailing of their connections. This study has highlighted the importance of selecting appropriate connector types, whether pinned, fixed, or semi-rigid, based on the required load path and deflection limits. The use of extruded steel brackets, such as fin plates and shoe brackets, provides both structural reliability and fabrication efficiency. Thermal considerations are essential in curtain wall design, as temperature-induced movement can lead to stress accumulation and failure if not properly accommodated. The integration of slotted holes and expansion joints ensures continued serviceability under thermal loading.

For vertical-to-floor and beam connections, challenges related to limited depth and deflection control were addressed using kicker brackets and steel inserts. These solutions help meet both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) requirements. Anchorage design remains a critical aspect, especially in systems that involve brittle materials such as glass. Factors such as edge distance, embedment depth, concrete strength, and anchor type significantly influence system safety. The use of interaction equations and concrete breakout models ensures reliable performance under combined loading. Finite Element Analysis (FEA) has proven to be an effective tool for validating connection behavior and optimizing design. As sustainable building practices continue to evolve, research such as that by Fernando et al. [29] underscores the importance of integrating advanced façade technologies with structurally sound and adaptable connection methodologies to meet both environmental and performance standards. This study offers practical, code-compliant design recommendations and highlights areas for further investigation, particularly in parametric optimization and advanced simulation for custom bracket geometries.

List of Abbreviations and Symbols

Abbreviations

Symbol / Abbreviation	Definition / Description
ACI	American Concrete Institute
BIM	Building Information Modeling
CF	Concrete Failure
CW	Curtain Wall
EC2	Eurocode 2 – Design of Concrete Structures
EN	European Norm
EIFS	Exterior Insulation and Finish System
ETA	European Technical Assessment
FEA	Finite Element Analysis
HIT	Hilti Injection Technology (Chemical Anchor System)
HST	Hilti Screw Threaded Anchor
MPa	Megapascal
NRd, NRk	Design / Characteristic Resistance
SLS	Serviceability Limit State
ULS	Ultimate Limit State
UHPC	Ultra-High Performance Concrete
VM	Von Mises (Stress Criterion)
PROFIS	Hilti PROFIS Engineering Software Suite
FiXperience	Fischer Anchor Design Software Suite
T-bolt	T-shaped bolt used in Anchor Channels
RHS	Rectangular Hollow Section
TR	Technical Report (e.g., TR029 – Design of Post-installed Fasteners)

Declarations

Funding

This research received no external funding.

Availability of Data and Materials

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

Use of AI Tools

Artificial intelligence tools were used to assist with grammar correction, language refinement, and clarity enhancement. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Competing Interests:

The authors declare that they have no competing interests that could influence the interpretation or presentation of the results reported in this manuscript.

Acknowledgment

Not applicable.

CRediT authorship contribution statement

Muhammad Tayyab Naqash (MTN): Conceptualization, structural analysis, connection design, manuscript drafting, and technical review.

Antonio Formisano (AF): Methodology, analytical validation, critical reviewing, and preparation of the final draft.

Ehsan Noroozinejad Farsangi (EF): Supervision, analytical validation, comprehensive review, and approval of the final manuscript.

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