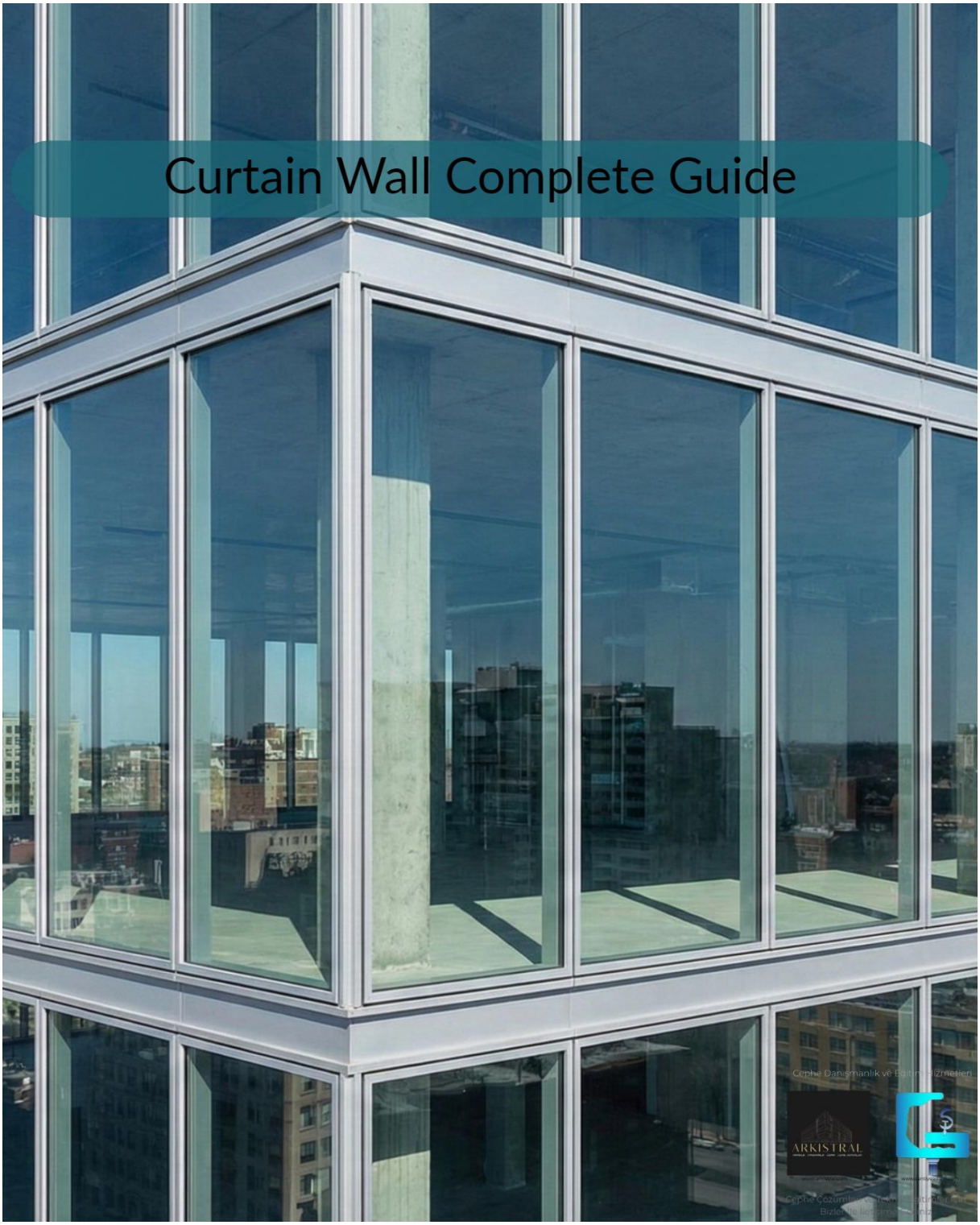
1. CURTAIN WALL SYSTEMS

This chapter introduces the fundamental concept of curtain wall systems, examines their historical evolution, and explains how they developed into today's advanced façade technologies. It also presents the core classification of curtain wall systems and establishes the technical framework that shapes modern design and implementation decisions.



1.1 Definition and Historical Development of Curtain Wall Systems

The concept of the curtain wall originates from the idea of a lightweight exterior skin positioned in front of the building's structural frame. Unlike traditional masonry façades, a curtain wall does **not** carry any vertical loads from the building. It supports only its self-weight and transfers all environmental actions—wind, seismic forces, temperature variations, and live loads—directly to the main structural frame.
In short, a curtain wall is an **independent, non-load-bearing exterior enclosure**.

According to the European standard **BS EN 13830**, a curtain wall is defined as:

"A self-supporting external façade system that transfers dead loads, environmental loads (snow, wind), seismic actions, and imposed loads to the primary structure of the building."

1.1.1 Historical Background

In the late 19th century, large-span greenhouses built to maximize daylight drove the pairing of iron and glass. By 1892, with the invention of the elevator and rising land prices in Chicago, high-rise construction accelerated rapidly. Steel-framed buildings replaced massive exterior walls, giving rise to the concept of **a structural skeleton independent from its external skin**.

One of the most iconic examples of this transformation is the *Reliance Building* by Burnham & Root. It represents the first clear separation of load-bearing structure and façade, marking the dawn of the modern curtain wall.

Some historical sources also consider Joseph Paxton's **Crystal Palace (1851)** as the earliest curtain wall prototype, where iron frames carried large glass surfaces to create a lightweight exterior envelope.

1.1.2 Development of Modern Façade Technology

By the early 20th century, heavy exterior walls were replaced with lightweight, modular, non-load-bearing façade systems. Architectural pioneers such as **Walter Gropius, Mies van der Rohe, and Peter Behrens** advanced the use of aluminum and glass in buildings.

As the mechanical performance of glass improved, curtain walls became the preferred façade solution for tall buildings. The first notable high-rise application of a curtain wall was **Lever House in New York (1952)**. Many geometric principles developed during this era still influence today's profile designs.

1.1.3 Post-War Industrial Expansion

Following World War II, rapid urbanization increased the need for fast, economical façade systems. This period marked the significant rise of modular aluminum-and-glass curtain wall systems.

Technological progress in metallurgy produced lightweight, durable materials such as stainless steel and aluminum. Concurrently, window technology evolved alongside façade systems; profile sections were redesigned to enhance structural resistance and thermal performance.

1.1.4 Transformation After the Energy Crisis

The energy crisis of the 1970s brought energy efficiency to the forefront of architectural design. As a result, innovations such as:

- Double-glazed units (DGUs)
- Insulated glass units (IGUs)
- Solar-control coatings
- Highly reflective external surfaces

became widespread.

These advancements helped reduce solar heat gain while improving indoor comfort.

From the 1990s onward, increased awareness of energy conservation accelerated the development of **double-skin façades**, which offer:

- Natural ventilation
- Enhanced solar control
- Pressure equalization
- Improved thermal comfort

These systems elevated the curtain wall from a passive enclosure to an **active façade solution** that optimizes energy performance and indoor environmental quality.

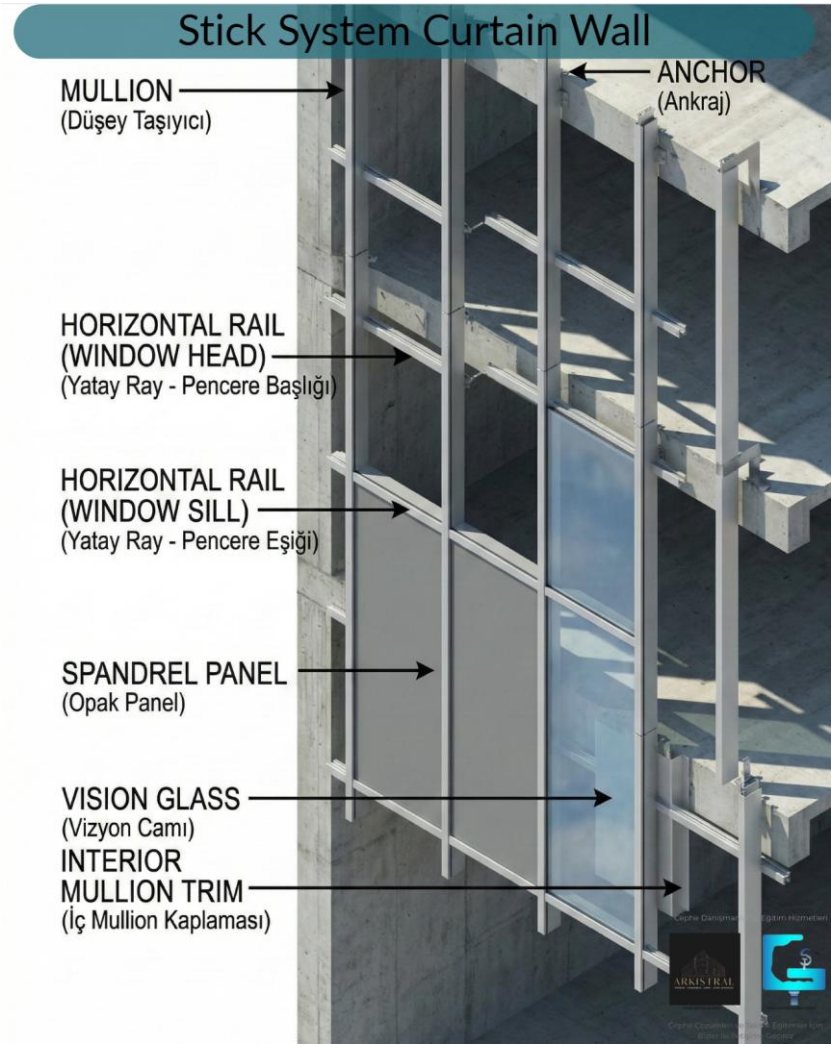
1.2 Classification of Curtain Wall Systems by Construction Method

Curtain wall systems are categorized into three primary groups based on production and installation methods:

- **1.2.1 Stick System Curtain Wall**
- **1.2.2 Unitized System Curtain Wall**
- **1.2.3 Mullion & Unit (Hybrid) System**

Below is the detailed explanation of the first category.

1.2.1 Stick System Curtain Wall



In the stick system, vertical mullions and horizontal transoms are assembled on-site to create the façade frame. Although profiles are pre-fabricated and pre-finished in the factory, the actual installation is performed on the building according to grid lines and axis references. Glass units and infill panels are then inserted into the completed frame.

Typical installation steps include:

1. Installing anchors on slab edges and required locations.
2. Fixing vertical mullions to the anchors.
3. Attaching horizontal transoms to the mullions.
4. Adjusting sliding connections to accommodate wind load, seismic movement, thermal expansion, and deflection.
5. Installing glass units and infill panels.

Advantages:

- Lower material cost due to standard profiles
- Reduced transportation cost
- Offers flexibility for on-site adjustments

Disadvantages:

- On-site assembly slows construction and increases labor cost
- Performance depends heavily on workmanship
- Not ideal for very tall or large façades; better suited for low- and mid-rise buildings

1.2.2 Unitized System Curtain Wall



In unitized systems, all façade units are fully fabricated and pre-assembled in the factory under controlled conditions. Each unit is generally **one story tall** and produced according to the project's modular width (Boswell, 2013).
This approach significantly increases production quality and minimizes site work.

Installation Process

Following the procedure outlined by **BCI Architectural Glazing & Building Enclosures**, installation typically proceeds as follows:

1. **Anchor points are located** according to architectural grid lines.
2. **Embedded channels are placed** in the concrete slab; brackets are installed onto the channels.
3. **Connector components** (T-bolts, anchor screws) are inserted and tightened.
    - In Turkey, embedded channels are rarely used due to labor intensity; brackets are usually fixed directly to the slab.
4. **Panels are lifted into place** using cranes or davits positioned on upper floors.

5. **Panels are hung on brackets**, aligned with adjacent units, and secured with bolts.
6. **Joints are sealed** using silicone, gaskets, and sealants (Ascher, 2013).

Figure 2.4 illustrates a typical unitized façade assembly.

Advantages of Unitized Systems

- Rapid installation → majority of work completed in factory
- High production quality due to controlled environment
- Reduced on-site workforce requirements
- Ideal for tall buildings
- Designed to accommodate inter-story drift and lateral movement (CMHC, 2004)

Disadvantages

- Heavy units require cranes and specialized lifting equipment
- Protection during transport and storage increases cost
- Mullion-to-mullion interlocks may limit the ability to create access openings
- Replacing damaged panels is more challenging than in stick systems (Boswell, 2013)

1.2.3 Mullion & Unit (Hybrid) Curtain Wall System

The mullion & unit system is a hybrid configuration that combines the principles of both stick-built and unitized curtain wall systems. Although it was once preferred in projects requiring deep mullion sections, its use today has become relatively limited.

Installation Process

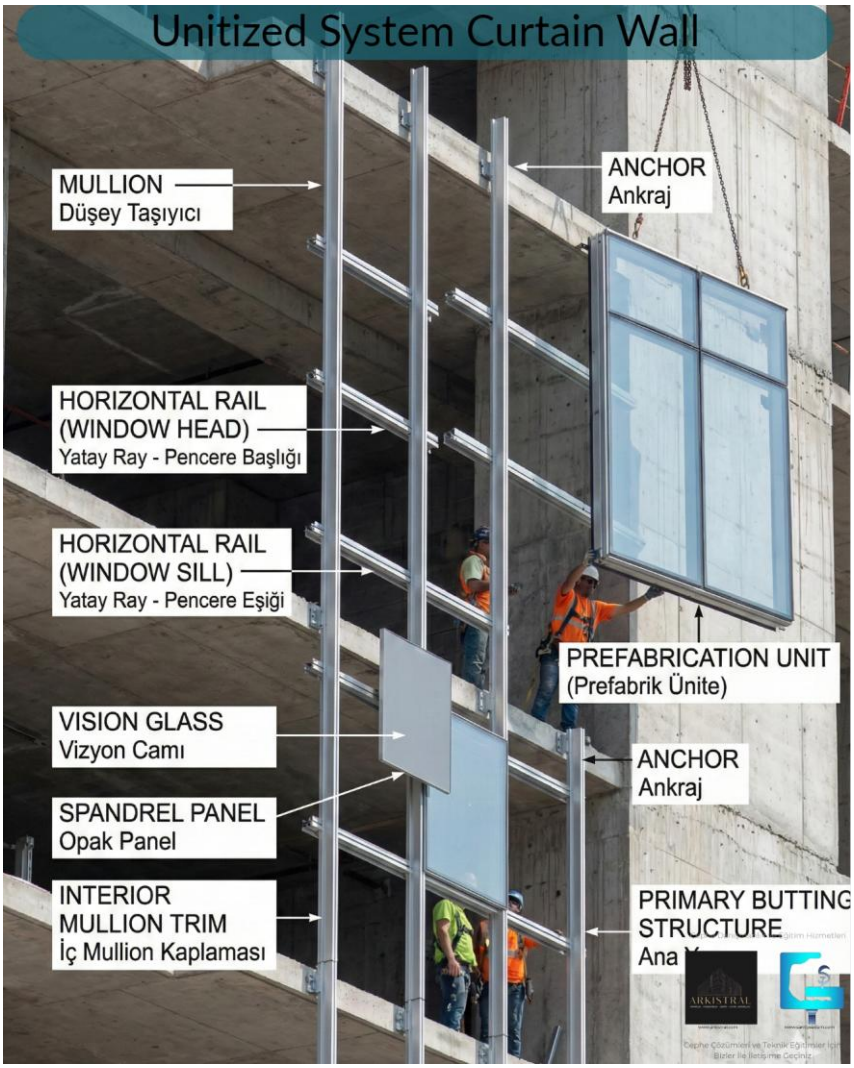
1. **Vertical mullions**, typically full-story height or taller, are installed first.
2. **Factory-preassembled frame units** are then placed between the mullions (Figure 2.5).
3. These units may be manufactured as a single full-height panel or separated into two components: a **vision panel** for the viewing zone and a **spandrel unit** for the opaque area (Auer, 2014).

Advantages

- Maintains many of the quality and speed benefits of unitized systems.
- Offers greater flexibility than stick systems when an opening is required, such as **maintenance access zones**.

Disadvantages

- Requires more on-site installation labor.
- Additional mullion connections extend the installation duration.
- Extra connections may increase labor costs.



1.3 Classification of Curtain Wall Systems According to Glazing Method

Curtain wall systems can also be categorized based on their glazing method. The three primary glazing types are:

- **1.3.1 Structural Silicone Glazing (SSG)**
- **1.3.2 Pressure Plate System**
- **1.3.3 Point-Fixing System**

Below is the detailed explanation of the first glazing method.

1.3.1 Structural Silicone Glazing (SSG)

Structural Silicone Glazing is a façade system in which the glass is bonded to the aluminum frame using a high-performance structural silicone sealant (Figure 2.6). The integrated bond between the glass, frame, and silicone provides the primary resistance to external loads.

This method is widely used in **high-rise buildings** due to its clean aesthetics and its capacity to manage lateral loads effectively.

Key Features of SSG

- The glass is bonded to the frame **without mechanical retainers**, such as clips, beads, or pressure plates.
- The continuous silicone bead resists **shear, tensile, and stress forces** along the entire perimeter.
- The glass panel can act as an **in-plane diaphragm**, helping to distribute lateral forces.
- This behavior provides significant advantages in **corner conditions**, where forces tend to intensify (ASCE, 2013).

Types of SSG Systems

According to the Canadian CMHC Guide (2015), SSG systems are classified into two types:

1. Two-Sided SSG

- Two edges of the glass are bonded with structural silicone.
- The other two edges are mechanically retained with pressure plates (Figure 2.7).

2. Four-Sided SSG

- All four edges of the glass are bonded using structural silicone.
- The **glass dead-load** is supported by a metal fin and **setting blocks** beneath the unit.

1.3.2 Pressure Plate System

The pressure plate system is one of the most widely used glazing solutions in architectural curtain wall design. The fundamental principle is the mechanical clamping of the glass unit onto the aluminum structural frame using **pressure plates**.

According to the CMHC Best Practice Guide (2015):

"Pressure plates must provide sufficient compression on the glazing gaskets when screws are tightened to the specified torque. The glazing pocket must include at least three weep holes for drainage."

A conventional pressure plate façade consists of:

- Mullion (vertical member)
- Transom (horizontal member)
- Glass unit
- Pressure plate
- Cover cap

Main Subtypes of Pressure Plate Systems

1. Standard System

- Cover caps are used on **both vertical and horizontal** directions.

- The caps serve two purposes:
    - Conceal the pressure plates and fasteners
    - Protect the drainage holes on the horizontal plates

2. Two-Sided (Hybrid) System

- Cover caps are used **only in one direction** (either vertical or horizontal).
- The other direction is sealed with structural silicone.
- This configuration produces a more refined, lighter appearance (Doğan, 2013).

3. Four-Sided Silicone System

- Silicone is applied to all four edges, eliminating cover caps entirely.
- Visually, this creates a continuous, glass-like façade similar to SSG systems (Winxie, 2007).

This variety allows architects to achieve different aesthetic expressions and performance goals.

1.3.3 Point-Fixing Glass System

The point-fixing system is designed to maximize transparency by minimizing the amount of visible structural support. In this method, loads are transferred from discrete points on the glass surface to the supporting structure.

Typical Support Components

- **Spider fittings** (multi-arm stainless steel connectors – Figure 2.9)
- **Steel cable nets**
- **Tension rods or tension trusses**

These connection points absorb static and dynamic loads and transmit them safely to the structural frame.

Structural Considerations

- Because the system prioritizes transparency and minimal hardware, **detailed structural analysis is essential**.
- Excessive lateral loads can cause glass **deflection and surface bending**.
- Therefore, glass type, thickness, and anchor arrangement are critical design parameters (Bertan, 2016).

For safety, **tempered and laminated glass** is commonly used to preserve integrity even in the event of breakage.

1.4 Classification of Curtain Wall Systems According to Façade Skin Configuration

Curtain wall systems can be categorized into three groups based on the configuration of their external skin:

1. **Single Skin Façade**

2. **Double Skin Façade (DSF)**
3. **Integrated Façade Systems**

1.4.1 Single Skin Façade

As the name suggests, a single skin façade consists of a single exterior layer and can be constructed using either stick-built or unitized techniques.

Glazing configurations commonly used in single skin façades include:

- **Structural Silicone Glazing (SSG)**
- **Pressure Plate Systems**
- **Point-Fixed Glazing Systems**

Kloft & Eisele (2002) note that single skin façades offer limited performance compared to DSF systems, particularly in:

- Night-time natural cooling in summer
- Reducing exterior wind pressure fluctuations when internal windows are open
- Lowering wind speeds at openable window locations
- Allowing shading devices to operate independently of strong wind exposure

1.4.2 Double Skin Façade (DSF)

Although the concept of the Double Skin Façade emerged early in the 20th century, its true development accelerated after the 1990s. Today, DSF systems are especially widespread throughout Europe.

One of the most comprehensive definitions is provided by Oesterle et al. (2001):

"A Double Skin Façade is a multi-layered building envelope composed of an inner and outer façade, separated by a ventilated cavity functioning as a controlled buffer zone for solar protection and air circulation."

Ventilation Strategies

DSF systems can be ventilated in three primary ways:

- **Natural ventilation**
- **Mechanical ventilation**
- **Hybrid ventilation**

The selection depends on climate, building height, prevailing winds, and performance goals:

- In **cold and temperate climates →** natural ventilation is preferred
- In **hot climates →** mechanical ventilation is more common

- A mixed approach is often adopted: natural ventilation in winter and mechanical ventilation in summer

The cavity depth varies significantly depending on design goals and can range from **200 mm to over 2 meters** (Chan, 2009).

Performance Characteristics

According to Aksamija (2013) and related research, Double Skin Façades provide several core benefits:

- Enhanced solar control and effective daylight penetration
- Reduced energy consumption
- Improved thermal comfort through buffer-zone insulation
- Reduced HVAC system size and operational load
- Lower impact of wind and microclimatic forces on the façade

The main drawback is the **higher construction cost** compared to single skin façades.

Types of Double Skin Façades

Based on the division and organization of the cavity, DSF systems fall into four primary categories:

1. Box Window System

The cavity is divided into small, independent modules using vertical and horizontal partitions.

Typical applications:

- Areas requiring **advanced noise control**
- Buildings with **specific acoustic performance requirements**
- Façades designed for **controlled natural ventilation**

2. Shaft Box System

A series of vertically interconnected box modules.

Advantages include:

- Reduced number of exterior openings
- Utilization of **thermal uplift** (stack effect)
- High acoustic performance

3. Corridor-Type DSF

A continuous horizontal cavity is provided for each floor.

Key performance benefits:

- Maximum natural ventilation
- Fire safety through compartmentalized floor-by-floor airflow
- Enhanced noise reduction
- Independent airflow for each story

4. Multi-Story DSF

A large, unpartitioned vertical cavity between the inner and outer façade.

Main characteristics:

- Air intake may be positioned at the top with exhaust at the bottom (or vice versa)
- Often supported by mechanical ventilation systems
- Suitable for buildings located in **high noise environments**

Shading Devices

Shading elements in DSF systems are usually placed **within the cavity**.
Louvered systems behave almost like an airtight façade when closed, while open louvers enhance natural airflow (BBRI, 2004).

Glass Selection

- **Inner layer →** typically double or triple insulated glazing
- **Outer layer →** usually a single pane of **tempered or laminated glass** (Poirazis, 2004)

Sustainability Considerations

Double Skin Façades are recognized as an essential passive design strategy for reducing energy consumption in high-rise buildings.

The cavity's **buffer-zone microclimate** can be used to regulate heat gains and losses.
Natural ventilation in tall buildings significantly reduces cooling loads (Harrison, 2003).

1.5 Components of Curtain Wall Systems

A curtain wall is a complex façade system composed of multiple interdependent components. These elements collectively provide environmental protection while safely transferring all imposed loads to the primary structural frame of the building.

In general, curtain wall components can be grouped into three main categories:

1. **Load-bearing components:**
   Aluminium framing profiles (mullions and transoms) and anchorage systems
2. **Infill components:**
   Transparent or opaque surface materials such as glass, metal panels, or stone cladding
3. **Sealing and insulation components:**
   Sealants, gaskets, mastics, and thermal/air–vapour barriers

(Figure 2.12 illustrates the general arrangement of these components.)

1.5.1 Framing System

The **framing system** forms the structural backbone of the curtain wall. All loads originating from glass and infill panels are first transferred to the frame members and then to the primary building structure. For this reason, the framing members must be correctly dimensioned both in terms of strength and deformation behaviour.

The frame typically consists of:

- **Vertical members (mullions)**
- **Horizontal members (transoms)**

These are usually made of **aluminium** or **steel**. Material selection depends on several key parameters:

- Architectural intent and profile geometry
- Module spacing and span lengths
- Wind, gravity, and seismic loads
- Grid configuration of the façade

In conventional curtain wall assemblies, aluminium framing members act as an integrated system together with the glass units. Mullions and transoms are not just simple load-bearing sections; they also incorporate:

- Pressure plates
- Snap-on or clip-on cover caps
- Internal stiffeners
- Fixing and connection channels

(see Figure 2.13).

Aluminium profiles can be manufactured in different depths for both vertical and horizontal elements. One of the major architectural advantages of aluminium is that **project-specific cross-sections** can be produced relatively easily through extrusion, allowing for highly optimized custom designs. The overall system depth is typically governed by **wind load** and **deflection limits** rather than by ultimate strength (ASCE, 2013).

With the advancement of façade technology, aluminium profiles have been developed with:

- Thinner wall thicknesses,
- Optimised cross-sectional geometry,

resulting in:

- Reduced overall weight of the curtain wall,
- Lower loads transferred to the primary structure,
- More economical façade solutions.

However, aluminium has a clear disadvantage compared to steel: its **modulus of elasticity is approximately one-third that of steel**, meaning it exhibits **larger deflections under the same load**. In curtain wall design, deflection limits often govern the sizing of members before ultimate load capacity is reached.

For this reason, project specifications typically define strict limits for:

- Out-of-plane deflection due to wind load, and
- In-plane deflection due to self-weight and other actions.

These limits are essential to:

- Prevent glass from disengaging from the mullion pocket,
- Avoid glass breakage,
- Maintain long-term performance of gaskets and weather seals.

Steel-Framed Systems

Steel support structures can be used within curtain wall systems in two principal ways:

- As individual members in a **stick-built logic** (Figure 2.14)
- As larger **combined structural elements**, such as trusses, pipe trusses or space frames spanning long distances

Horizontal steel members are frequently used to carry stone or heavy cladding panels in modular systems, while vertical steel trusses can be placed behind large glazed areas to support wide spans.

Additionally:

- **Steel cables** may be used as primary load-bearing elements in **cable-net façades**, where maximum transparency is desired.
- In these systems, the allowable deflections are considerably larger than in conventional aluminium-framed façades. However, this makes glass selection and connection detailing significantly more critical.

Using steel support systems allows:

- Larger spans without intermediate supports,
- The use of larger glass panels,

- High stiffness with relatively slender sections.

In terms of strength and durability, steel profiles:

- Exhibit higher resistance to impact and local crushing,
- Perform better against scratching and mechanical damage,
- Can be combined with **stainless steel cover profiles** to enhance both aesthetics and corrosion resistance (Naqash, 2016).

In many contemporary solutions, a **composite approach** is preferred:
Steel is used as a **concealed reinforcement** inside the aluminium profile, while the glass is still supported by the extruded aluminium glass pocket (CMHC, 2013).

Vertical mullions and horizontal transoms are commonly connected via extruded **connector channels**. Some of these connections are designed to transfer **bending moments**, while others are detailed as **slotted or sliding connections** intended to transfer only shear forces, thereby accommodating thermal movements and interstorey drift.

Pressure Plates, Cover Caps and Fasteners

The framing system is not limited to mullions and transoms; **pressure plates, cover caps and mechanical fasteners** also play key roles in overall performance.

Pressure Plate

The pressure plate is the component that clamps and secures the glass unit from the exterior. In some façade designs it may be partially or fully replaced by structural silicone in alternative glazing systems. Typically:

- It is made of the same material as the frame (usually aluminium).
- Vertical pressure plates are installed in segments along the mullion.
- Horizontal pressure plates are installed with end gaps to accommodate thermal expansion.
- Pre-drilled holes are provided for fixing screws, usually at spacings of approximately **150–200 mm**.
- Drainage and ventilation (weep) holes are provided in horizontal pressure plates; their size and spacing are determined by project-specific detailing (CMHC, 2013).

Cover Cap (Snap Cap / Cover Profile)

In pressure plate systems, the cover cap is the **visible external finishing element**:

- It conceals the pressure plate and fixing screws.
- It provides additional protection to the drainage openings in horizontal pressure plates.
- With different forms and widths, it can significantly influence the architectural character of the façade.

Cover caps can be produced from aluminium, stainless steel, copper or other metals. In design, **thermal expansion** of these profiles must be carefully considered and appropriate **splicing details** must be provided at joints.

Fasteners

Screws, bolts and nuts are used to:

- Connect frame components to each other,
- Fix pressure plates to the framing,
- Attach the curtain wall to the primary structure via anchors and brackets.

For exterior exposed locations and pressure plate fixings, **stainless steel fasteners** are generally preferred. In protected interior locations behind the air barrier, coated carbon steel fasteners may be used, provided that adequate corrosion protection (plating, polymer coating, etc.) is ensured.

1.5.2 Infill Components

The infill components of a curtain wall form the most visible portion of the system and largely define its architectural expression. These elements may include:

- **Glass units**
- **Opaque panels** (stone, metal panels, composite panels, etc.)
- **Special cladding or coating systems**, where required

In contemporary curtain wall design, the overall character of the façade is predominantly determined by the **glazed surface**.

Glass in curtain walls has several primary functions:

- Transmitting daylight into the interior
- Providing visual connection between inside and outside
- Ensuring the required thermal, solar and acoustic performance
- Meeting safety and fire behaviour requirements

Thus, glass selection must consider not only optical properties, but also:

- Thermal transmittance,
- Solar heat gain,
- Sound insulation,
- Impact resistance and fragmentation behaviour.

The most common glass types used in curtain wall systems are:

- **Insulating Glass Units (IGU)**
- **Safety glass (laminated and toughened)**

- **Coated glass (low-E and solar control)**
- **Opacified glass (spandrel glass)**

These are summarised below.

1.5.2.1 Insulating Glass

An **insulating glass unit (IGU)** consists of two or more glass panes separated by a sealed cavity filled with air or gas (Figure 2.15).

Key characteristics:

- The cavity width is typically in the range of **12–20 mm**.
- It may be filled with **air**, **argon**, or other higher-performance gases.
- The perimeter is hermetically sealed using **spacers** and **sealants** to ensure long-term airtightness.

The main functions of insulating glass are:

- Reducing heat transfer between interior and exterior,
- Improving sound insulation,
- Increasing energy efficiency, particularly when combined with solar control coatings.

Glass compositions are selected according to desired:

- Visible light transmittance,
- Solar heat gain coefficient,
- Reflectance,
- Acoustic performance.

Spacer type and sealant systems are also chosen in line with these performance criteria (CMHC, 2013).

The overall glass thickness and the thicknesses of individual panes must be calculated with particular attention to:

- Design wind loads,
- Panel dimensions,
- Acceptable deflection limits.

1.5.2.2 Safety Glass

Safety glass used in curtain walls generally falls into two main categories:

- **Laminated glass**

- **Toughened (tempered) glass**

Laminated Glass

Laminated glass is produced by bonding two or more glass panes with one or more **interlayers**, typically made of PVB (polyvinyl butyral) (Figure 2.16).

The interlayer thickness can vary from approximately **0.38 mm to 2.28 mm**, depending on performance requirements (ASCE, 2013).

Key advantages of laminated glass:

- In case of breakage, glass shards adhere to the interlayer instead of falling away, reducing the risk of injury.
- It significantly reduces UV transmission, slowing the fading of interior finishes.
- Coloured interlayers can be used to achieve specific aesthetic effects.
- With special acoustic PVB interlayers, it provides superior sound insulation.
- It can be used as a **monolithic pane** or as part of an **insulating glass unit**.

Toughened (Tempered) Glass

Toughened glass is a flat glass that has undergone a controlled **heat treatment**:

1. The glass is heated to a high temperature,
2. Then cooled rapidly in a controlled manner.

As a result:

- Its bending and impact strength can reach **4–5 times** that of ordinary annealed glass.
- Its fragmentation pattern changes: upon breakage, it shatters into small, relatively harmless particles, reducing injury risk.

Furthermore, toughened glass:

- Has high resistance to **thermal shock**,
- Performs better under rapid temperature changes (Garg, 2007).

In modern curtain walls, these two safety glass types are indispensable, especially in:

- High-rise buildings,
- Areas with intensive human use,
- Locations where post-breakage safety is critical.

1.5.2.3 Coated Glass

Growing demands for energy efficiency in the glass industry have led to the development of advanced **coated glass technologies**. The two most common groups used in curtain wall applications are:

- **Low-emissivity (Low-E) glass**
- **Solar control glass**

Low-E Glass

Low-E glass is designed to **reduce heat transfer** between interior and exterior spaces (Figure 2.17). Thanks to a thin metal-oxide coating:

- Heat loss from interior to exterior is reduced,
- Unwanted heat gain from outside to inside is limited.

Two principal strategies exist:

- In **cold climates**, the coating is often placed on an internal surface of the IGU to retain interior heat and reduce heating loads (Patterson, 2008).
- In **hot climates**, coatings are positioned to limit solar heat gain, helping to keep interiors cooler in summer while maintaining balanced conditions in winter (Tortu, 2006).

Low-E glazing systems aim to maintain high daylight transmittance while significantly reducing thermal losses.

Solar Control Glass

Solar control glass is widely associated with the characteristic **reflective appearance** of many high-rise façades (Figure 2.18).

Typical features:

- Metallic oxide coatings provide high solar reflection,
- Various metallic colour tones such as **gold** or **bronze** can be achieved,
- The coating may be located on the inside or outside surface depending on the desired visual and performance effects.

The main objectives are:

- Reducing solar heat gain and glare,
- While allowing sufficient visible light transmission into the interior.

Garg (2007) notes that such coatings reduce both heat gain and glare while preserving transparency and lowering cooling loads.

1.5.2.4 Spandrel / Opacified Glass

Spandrel glass is an opacified glass type used to conceal structural elements such as:

- Columns, beams,
- Slab edges,
- Mechanical or service zones

(Figure 2.19).

Typical applications:

- Opaque horizontal bands between floors,
- Areas where the floor slab should not be visible from outside.

Characteristics:

- Glass should be heat-treated (tempered or heat-strengthened) depending on the expected thermal stress level.
- Opacity is achieved by applying a **ceramic frit** or **silicone-based coating** on the interior surface.
- It can be produced in a wide range of colours, making it an important aesthetic tool in façade design.

Grün Consulting (2020) reports that a typical spandrel panel may provide an R-value in the range of **0.5–0.8 m²K/W**, which can be less than one-fifth of the required total thermal resistance in many projects. Consequently, additional insulation layers are often necessary in spandrel zones for high-performance façades.

1.5.3 Anchors

Anchors are critical components that connect the curtain wall frame to the primary structural system. Improper design or installation of these elements can compromise the safety and performance of the entire façade.

In general, anchors can be divided into two main categories:

- **Fixed anchors** that resist both gravity and lateral loads
- **Slotted / sliding anchors** that primarily resist lateral loads while allowing controlled movement

Each anchor assembly typically comprises two main parts (Figures 2.20–2.21):

1. **Embedded element (embed):**
   Steel component cast into the concrete slab edge or fixed later using chemical or mechanical anchors.
2. **Mounting lug / bracket:**
   Connects the embedded element to the curtain wall frame.

Anchor type and capacity must be determined with respect to:

- Design wind load at the relevant elevation,
- Overall building height,
- Location of the façade (corner zone, edge zone, internal bay, etc.).

Even within the same project, different façade zones may require different anchorage types.

Channel Anchors and Practice in Turkey

One of the most robust and adjustable solutions is the **channel anchor system**:

- A steel channel is cast into the concrete slab edge,
- The façade bracket is fixed within the channel and adjusted to its final position,
- The system provides excellent performance under seismic and wind-induced movements.

However, in practice—particularly in Turkey—this method:

- Is considered time-consuming,
- Requires high-precision workmanship,

and therefore many contractors tend to prefer:

- **Directly welded or bolted plates** to the slab,
- **Mechanical or chemical anchors** with welded angles or plates.

Traditional approaches commonly rely on mechanical or chemical anchors, welded steel plates and stud-welded elements to transfer forces to the concrete structure.

In recent years, **friction-based mechanical anchor bolts** have become increasingly popular due to:

- Faster installation,
- Greater adjustability,
- Reduced intervention in the concrete structure (Halfen, 2014).

MBY Engineering (2019) recommends that the maximum design load per individual anchor should not exceed **20 kN**, and that the bracket thickness should typically be selected within the range of **6–15 mm**, depending on load levels and detailing.

Doğan (2013) emphasizes that, especially in high-rise buildings, positional tolerances at anchor points must be extremely tight; otherwise, small execution errors at lower levels can lead to significant cumulative misalignments and detailing problems as the building rises.

1.5.4 Sealants

Sealants are among the most critical components of a curtain wall system. As one of the primary barriers between the building and the exterior environment, they prevent the ingress of water and air. For this reason, a sealant is not merely a “gap filler,” but a safety-critical component that directly affects the overall performance of the façade.

The most important characteristic of a sealant is its **movement capability**. It must be able to elastically absorb cyclic movements caused by:

- Temperature changes
- Humidity variations
- Sound and vibration
- Wind pressure and suction

According to CMHC (2013), sealants can be classified by movement capability into three groups:

- **Low-range movement sealants**
- **Medium-range movement sealants**
- **High-range movement sealants**

In general:

- **Lower cost → lower movement capability → shorter service life**
- **Higher cost → higher performance → longer service life**

Figure 2.22 illustrates various sealant types.

Low-Range Movement Sealants

Low-range movement sealants are used only in very limited locations in modern curtain wall systems.

Reasons include:

- Limited movement capability
- Typically used in concealed locations within the system that are not exposed to UV radiation
- Often applied in inaccessible internal regions where replacement is difficult
- Generally based on oils and resins, with mineral fillers

Due to long service life expectations in contemporary façades, low-range sealants are rarely preferred.

Medium-Range Movement Sealants

Medium-range movement sealants are also used only in specific situations. They are more appropriate for:

- Non-moving joints
- Around back-pans
- At accessory interfaces
- In interior locations not exposed to UV radiation

In these applications, the sealant accommodates deformation mainly through **creep and plastic deformation**, rather than true elastic movement. Consequently, medium-range sealants are **not suitable** for high-performance exterior weather joints.

High-Range Movement Sealants

High-range movement sealants are the most commonly used class in modern curtain walls. They include two main groups:

1. **Silicone-based sealants**
2. **Polyurethane-based sealants**

Silicone Sealants

Silicones are widely regarded as the **gold standard** in the curtain wall industry.

Key characteristics:

- Movement capability may reach **±70%**
- Excellent adhesion to most curtain wall components
- Outstanding resistance to **UV radiation** and **ozone**
- Suitable for long-term exterior exposure
- Used in demanding applications such as **structural silicone glazing (SSG)**

Disadvantages:

- Tendency to attract dust and dirt on the surface
- Certain types may exhibit slight oil bleed over time

Polyurethane Sealants

Polyurethane sealants can be used in a similar manner to silicones; however:

- Their movement capability is typically **below ±50%**
- UV resistance is generally inferior to silicone

For these reasons, façade contractors today almost always prefer **silicone sealants** for exterior weather-exposed joints, especially in curtain wall applications.

1.6 Performance Criteria of Curtain Wall Systems

The curtain wall is the most critical interface between the building and the external environment. It is directly exposed to:

- Wind
- Rain
- Temperature variations
- Humidity
- Solar radiation
- Fire
- Earthquake and other dynamic effects

The system must adapt to these changing conditions over time while ensuring **safety and comfort for occupants**.

In high-rise buildings, the façade is subjected to:

- Much higher wind pressures
- Increased local suction at building corners
- More severe driving rain effects
- Sudden thermal changes due to solar exposure

Therefore, curtain wall systems must satisfy international performance requirements for:

- Water tightness
- Air tightness
- Thermal performance
- Acoustic control
- Fire safety
- Structural strength and serviceability

Table 2.1 lists the relevant performance test standards.

In this context, performance requirements are typically examined under five main headings:

1. Structural integrity
2. Water, moisture and air control
3. Daylighting and thermal control
4. Control of sound transmission
5. Fire control

The first parameter, **structural integrity**, is discussed below.

1.6.1 Structural Integrity

Structural integrity is vital for any façade system, as the failure, detachment or breakage of any curtain wall component directly affects **life safety**. For this reason, stiffness, strength and controlled movement lie at the core of curtain wall design.

Curtain walls are subjected to two main categories of load:

Primary Loads (always considered):

- Dead load
- Wind load

Secondary Loads (case-dependent):

- Earthquake
- Impact loads
- Maintenance and cleaning platform loads
- Blast loads
- Loads from external sun-shading devices
- Temperature effects
- Snow load

(CMHC, 2013)

Wind Load and Deflection Limits

Wind load is one of the most decisive parameters in façade design. Wind pressure:

- Increases with **building height**
- Becomes more critical at **corners and edges**
- Directly influences:
    - Glass thickness
    - Frame depth and stiffness
    - Anchorage and connection details

Atalay (2006) notes that profile deflection limits are typically around **L/200** in many systems. Deformation limits therefore play a critical role in both glass and frame design.

For accurate determination of wind effects, the following are necessary:

- Calculation of wind pressure in accordance with the relevant codes,
- Structural modelling of façade components under realistic load conditions,
- Understanding of the three-dimensional load transfer mechanism within the façade (ASCE, 2013).

The BS EN 13830 (2015) standard requires that curtain walls must resist design wind loads **without permanent deformation**.

Wind resistance tests are carried out in accordance with **BS EN 12179**. According to this standard, the maximum visible deflection (d) of the frame is limited as follows:

- For **L < 3000 mm**:
  - d≤L/200d \leq L / 200d≤L/200
- For **3000 mm < L < 7500 mm**:
  - d≤5 mm+L/300d \leq 5 \text{ mm} + L / 300d≤5 mm+L/300
- For **L > 7500 mm**:
  - d≤L/250d \leq L / 250d≤L/250

Deflection calculations are performed using Equation (2.1).

Glass and spandrel panels must similarly be sized according to wind load and deflection criteria (Yalaz, Ünlü, Çelik, 2018).

Seismic Effects

Earthquakes produce two distinct types of response in curtain wall systems:

1. Motion of the façade panel due to its **own mass**
2. Motion induced by **interstorey drift** of the main building structure

As a result, the following problems may occur:

- Bending and buckling in frame members
- Glass breakage, especially at edges
- Pinching and jamming between panel and frame
- Deformation or yielding of anchor brackets

To mitigate these risks:

- Sufficient horizontal and vertical movement tolerance must be provided between frame and anchor,
- **Slotted or channel-type anchors** allowing differential movement should be used,
- **Setting blocks and spacer blocks** made of elastomeric materials should be placed between glass and frame (Arnold, 2016).

Doğan (2013) notes that **stick systems** tend to exhibit more flexibility than fully unitized systems during seismic events; the ability of movement to be distributed from one panel to another can be a significant advantage in stick-built façades.

Seismic load effects on curtain walls are discussed in detail in **Chapter 4** of this book.

Thermal Effects (Thermal Movement)

Temperature changes due to solar radiation introduce significant movements in:

- Cover caps,
- Aluminium framing members,
- Joint and sealant regions.

These movements may lead to:

- Bending or warping of cover caps,
- Separation or opening at cap joints,
- Fatigue and loss of performance in sealants and gaskets.

To avoid such problems, **expansion gaps and appropriate splicing details** must be provided at all critical joints.

Types of Movement

The main types of movement occurring within a curtain wall system include:

- Profile deflections due to wind load
- Seismic effects and interstorey drift
- Thermal expansion and contraction
- Long-term structural creep
- Building settlement and differential movements

Figures 2.23 and 2.24 illustrate expansion details in unitized and stick systems.

These movements do not only threaten the integrity of the system; they can also lead to:

- Noise and rattling,
- Metal fatigue,
- Sealant and gasket failures,

ultimately compromising the façade's weather performance (CMHC, 2013).

1.6.2 Control of Water, Moisture and Air

Two of the most critical performance issues in curtain wall design and construction are:

- **Water leakage**
- **Excessive air infiltration**

Even if a façade is structurally strong and capable of resisting wind loads, it cannot be considered high-performing if it fails to control water and unintended air flow.

According to BS EN 13830 (2015), **water tightness** is defined as:

The ability of the curtain wall to prevent rainwater penetration that may cause hygiene, health or functional problems in the indoor environment.

Water may enter the façade cavity, but must then be:

- Collected, and
- Drained back to the exterior in a controlled manner,

without reaching the interior occupied space.

Wind-driven rain typically does not act as discrete droplets; instead, it often forms:

- A film,

- Mist, or
- Spray pattern

over the façade surface and tends to accumulate at joints and discontinuities. This behaviour increases the risk of leakage at the weakest points of the system—namely joints and intersections.

Two Main Approaches to Water Control

There are two fundamental principles used to control water in curtain walls:

1. **Internal drainage systems**
2. **Pressure-equalized rain screen systems**

1. Internal Drainage System

In this approach:

- Any water entering the façade is collected in defined cavities or gutters,
- It is then discharged to the exterior through weep holes, slots or drainage channels.

This concept is especially common in **conventional pressure plate systems**. Attention must be paid to:

- Continuity of drainage paths,
- The risk of blockage in weep holes,
- Minimum slopes and proper detailing of gutters.

2. Pressure-Equalized Rain Screen System

This approach is based on the **rain screen principle** (Figure 2.25):

- An externally ventilated outer skin,
- A drained and ventilated cavity behind it,
- An interior **air barrier** that is as airtight as possible.

The objective is to minimize the pressure differential between:

- The outer skin, and
- The inner air barrier,

so that rainwater is not driven into the system by wind pressure.

For both internal drainage and pressure-equalized systems to function as intended:

- The behaviour of wind-driven rain must be well understood,
- Joint and interface details must be carefully designed,

- On-site workmanship must strictly follow the design documentation (Winxie, 2007).

Gaskets, Seals and Silicones

According to CWCT (2008), the critical components controlling air and water leakage in curtain walls are:

- **Gaskets**
- **Sealants**

Gaskets can be divided into two categories:

- **Static gaskets:** Used in non-moving joints where no relative movement is expected.
- **Dynamic gaskets:** Used around operable windows, doors and access panels where movement occurs.

Silicone applications generally serve two distinct purposes:

1. **Weather seal silicone**
    - Used in external joints to prevent air and water infiltration.
2. **Structural silicone**
    - Used to bond glass to supporting frames without mechanical glazing beads.
    - Enables flush, capless glass façades.
    - Also contributes to limiting water and air penetration at the joint region.

Condensation and Moisture Control

In details with poor thermal performance, temperature differences between interior and exterior can lead to **surface or interstitial condensation**. This may result in:

- Water droplets on interior surfaces,
- Mould and fungal growth on damp surfaces,
- Moisture accumulation in insulation layers.

Therefore, during design it is essential to assess:

- Why condensation may occur,
- At which locations it is likely to form,
- How it will be safely removed from the system.

To address these issues:

- A high-performance **vapour barrier** should be included in the build-up,

- This barrier is typically placed close to the line of gaskets and sealant on the warm side of the construction.
- **Spandrel zones** are generally more sensitive to moisture than clear glazed areas and must receive particular attention in interior detailing (Sanders, 2006).

EN 13830 (2015) emphasizes that vapour barriers used in opaque infill panels must be selected in accordance with the **hygrothermal conditions** of the building. In case condensation occurs, the system must allow water to:

- Be collected, and
- Be discharged to the exterior

without being trapped within the façade.

In Turkey, water tightness and air permeability performance of curtain wall systems is assessed in accredited laboratories according to the standards listed in Table 2.2.

1.6.3 Control of Sound Transmission

In dense urban environments, alongside highways or near airports and industrial zones, **reducing external noise** is a key performance criterion for curtain wall systems.

Thanks to its multi-layered build-up, a curtain wall can provide very good acoustic performance compared to traditional masonry walls. However, if not properly designed, glazed areas may become the **weakest link** in the overall sound insulation of the façade.

A typical acoustic design process includes:

1. Environmental noise assessment (traffic, aircraft, industrial noise, etc.)
2. Determination of the required minimum **sound transmission loss (TL)** or **STC (Sound Transmission Class)**
3. Selection of glass and spandrel build-ups
4. Design of framing profiles and joint details
5. Quality control of on-site installation

The acoustic consultant informs the façade designer about:

- The minimum required TL / STC values,
- The need to evaluate vision and spandrel zones separately,
- The critical frequency ranges in which performance is required (CMHC, 2013).

For glazing, the main parameters affecting STC are:

- Glass thickness,
- Number of glass layers (single, double, triple),
- Cavity width and filling between panes,

- Type of interlayer (especially **acoustic PVB** in laminated glass),
- Damping between layers.

Winxie (2007) points out that in many wall systems, the weakest elements are **glazed areas and openings**. Therefore, for projects with high acoustic requirements, façades should incorporate:

- Double or triple glazing,
- High-quality perimeter sealing,
- Acoustic separation between inner and outer layers of glass.

Spandrel zones are typically:

- Composite constructions consisting of metal panels, aluminium back-pans, stone or composite cladding, insulation layers and internal linings.
- As such, standard catalogue STC values for conventional walls cannot be directly applied.
- Full-scale mock-up tests are often necessary to verify real acoustic performance.

Ultimately, the acoustic design of curtain walls must be evaluated in accordance with the relevant national and international standards.

1.6.4 Fire Control

Fire performance is one of the most critical design criteria for curtain wall systems, particularly in high-rise buildings. The façade must be designed to:

- Prevent the spread of flames and smoke between storeys,
- In particular, prevent vertical fire spread at slab edges.

The fire reaction of façade materials is evaluated according to their **combustibility classification** ("non-combustible / combustible"). In curtain wall systems:

- The primary materials are generally **non-combustible**, such as:
    - Aluminium,
    - Glass,
    - Stone cladding, etc.
- Secondary components (gaskets, sealants, certain types of insulation) may be used **within defined limits**.

In high-rise buildings:

- Façade materials are generally expected to be **non-combustible**.

For low- and mid-rise buildings, at minimum, materials of **limited combustibility** or **hardly flammable** class should be specified.

To prevent the passage of flames and smoke between the floor slab and the curtain wall, the following elements are used (see Figure 2.26):

- **Fire stops**

- **Smoke seals**

The performance of these elements in a fire scenario depends on:

- The curtain wall remaining attached to the structure,
- The back-pan and insulation system remaining in place.

In other words, the fire-stopping material alone is not sufficient; the **entire interface detail must be designed as an integrated system**.

Fire performance must be verified in accordance with national building codes and relevant EN / ISO / ASTM-based fire test standards.

1.6.5 Daylight and Thermal Control

Heat and light are the two primary environmental effects transmitted into the interior through the curtain wall. Balancing these two is critical both for **occupant comfort** and **energy consumption**.

Key objectives are:

- To admit as much **useful daylight** as possible,
- To limit **unwanted solar heat gains**,
- To prevent overheating in summer while reducing heat losses in winter.

Shading Devices

One of the most common strategies for solar control is the use of **shading devices**. These may be:

- **Fixed**
- **Movable** (motorized or manually adjustable)

A typical orientation-based approach is:

- On **south-facing façades**:
    - Horizontal shading devices are generally more effective.
- On **east and west façades**:
    - The sun is at a lower angle, so vertical fins or screens are often preferred.

Movable shading systems:

- Can adapt dynamically to **daily and seasonal changes** in solar angle,
- And therefore are more efficient than fixed devices in many cases.

Standards **EN 13363-1** and **EN 13363-2** define calculation methods for:

- The **total solar energy transmittance**, and
- The **light transmittance** of glazing systems with shading devices.

In summer:

- Effective solar control helps maintain acceptable indoor temperatures and reduces cooling energy demand.

In winter:

- Benefiting from solar gains as much as reasonably possible helps reduce heating energy consumption.

Glass Coatings and Multi-Layer Glazing

As discussed earlier, surface treatments such as:

- **Low-E coatings**, and
- **Solar control coatings**,

play a major role in controlling both heat and light transmission through the glazed areas.

To enhance thermal performance, it is now common—also in Turkey—to use:

- **Double or triple glazing**,
- Gas-filled cavities (argon, krypton, etc.) instead of only dry air,
- High-performance spacer and edge-seal systems.

In many contemporary projects, **argon-filled double glazing** has become standard practice.

Thermal Control in Frames and Spandrel Zones

Heat losses do not occur only through the glass, but also through:

- The **framing system**, and
- The **spandrel zones**.

Therefore, it is essential to:

- Use **thermal breaks** in aluminium profiles,
- Ensure that the **thermal insulation layer is continuous** along the interior side of the façade,
- Minimize or eliminate **thermal bridges**,
- Carefully control condensation risk in spandrel zones, especially between insulation and metal back-pans.

In the spandrel area, the following must be considered as an integrated build-up:

- Adequate insulation thickness,
- A correctly positioned **vapour barrier**,
- A well-detailed **back-pan**.

If the design is incorrect, the spandrel zone may suffer from:

- Condensation,
- Mould growth,
- Significant loss of thermal performance.

1.7 Evaluation

In this chapter, curtain wall systems have been examined within a comprehensive framework, considering:

- Their **design and construction methods**,
- **Glazing types**,
- **Façade skin configurations**,
- Individual **components** and overall **performance criteria**.

First, the typology of systems was described, followed by detailed discussion of:

- The structural framing system,
- Glass and other infill components,
- Anchors,
- Sealants and gaskets.

Subsequently, curtain wall performance was analysed under the headings of:

- Structural strength and serviceability,
- Control of water, air and moisture,
- Daylighting and thermal management,
- Acoustic performance,
- Fire safety.

The principles presented in this chapter form the basis of façade designs that are later verified through both **experimental testing** and **computer simulations**. However, tests performed under laboratory conditions do not always replicate real site conditions exactly.

For this reason, in addition to codes and standards, the designer must also take into account:

- The realities of the construction site,
- The quality of installation works,
- Long-term maintenance and operation processes.

In the next chapter, **wind loads acting on curtain wall systems** will be examined in more detail, and design criteria will be discussed in terms of the **relationship between load and deformation**.

2. EFFECT OF WIND LOAD ON CURTAIN WALL SYSTEMS

Curtain wall systems form the **first external shield** of a building, meaning they are the elements most directly exposed to wind action. Façade engineers are well-aware that wind imposes major structural effects on the system; however, correctly defining these effects, calculating them according to standards, and transferring them into façade design is not always straightforward.

For this reason, the entire load transfer mechanism—from the moment wind pressure meets the façade surface to its final dissipation into the structural frame—must be fully understood (ASCE, 2013). Wind load must be traced through the following path:

- Initial contact on the façade panel
- Transfer to the surrounding support frame
- Vertical mullions and horizontal transoms
- Anchor brackets
- The primary structural system

This chapter discusses the concept of wind load in Turkey and around the world, with special emphasis on Istanbul's wind climate, its effects on mid- and high-rise façades, and how curtain wall components resist these actions.

2.1 Definition of Wind and Fundamental Concepts

Wind is the horizontal movement of air masses caused by atmospheric pressure differences. These movements flow from high pressure to low pressure, while surface roughness, topography, and temperature variations significantly influence wind speed and turbulence.

From a façade engineering perspective, wind creates two primary actions:

- **Positive pressure (windward):** Wind pushes against the surface.
- **Negative pressure (leeward):** Wind separates from the surface and creates suction forces.

Both effects may act simultaneously on different parts of the building envelope.

Wind Load

Wind load is the total lateral force exerted by wind on the façade. It must be safely transferred through:

1. Glass/panel surfaces
2. Mullion–transom framing
3. Anchors
4. The building's structural system
5. Foundations

The magnitude of wind load depends on wind speed, building height, building geometry, surface roughness, and local turbulence intensity.

Kloft & Eisele (2002) highlight a striking point:

“Local panel wind pressures may reach up to **500 kg/m²**, whereas global structural wind loads are often around **150 kg/m²**.”

Therefore, wind assessment is required at both **panel scale** and **structural scale**.

2.1.1 Vortex Shedding

As wind flows around prismatic elements—such as mullions, fins, and tubes—unstable pressure zones form on the leeward side. This results in:

- Alternating vortices shedding from the rear surface
- Periodic dynamic excitation on the element
- Increased structural vibrations

(F. Fu, 2018)

The vortex shedding frequency is expressed by the **Strouhal number (St)**:

St=D·fvUSt = \frac{D \cdot f_v}{U}St=UD·fv

Where:

- **D** = characteristic width of the element
- $\mathbf{f_v}$ = vortex shedding frequency
- **U** = wind velocity

Vortex shedding becomes critical in slender façade elements, fins, cable-supported systems, and exposed mullions.

2.2 Wind Drift Design

Most national and international building codes specify limits for **storey drift** (relative lateral displacement between floors). These limits exist to ensure that:

- Façade cladding is not damaged
- Interior partitions do not crack
- P–Delta effects do not amplify dangerously

In some codes, drift limits are mandatory; in others, they serve as design guidelines. For curtain wall engineering, **drift behaviour is a key design parameter**.

2.3 Wind Loads in Turkey and Istanbul Analysis

Interviews with multiple façade consultants reveal that Turkey lacks a fully detailed national wind map specifically tailored for façade design. Therefore, engineers often use:

- **Basic wind speed values**
- Local engineering experience
- Municipality-provided limit values

Basic Wind Speed for Istanbul

According to **İYBRY (2009)**, based on 1-minute interval measurements at Istanbul Atatürk Airport, the basic wind speed is:

V=25 m/sV = 25 \, m/sV=25m/s

Minimum design wind pressure for façade elements is:

0.5 kN/m20.5 \, kN/m^20.5kN/m2

Typical average wind speeds in Istanbul:

- **European Side:** 5.5–6.5 m/s
- **Asian Side:** 6.5–7.5 m/s

Prevailing wind directions:

- European Side → **NNE**
- Asian Side → **NE–NW**

These parameters are critical, especially for high-rise buildings.

2.4 Wind Behaviour on Mid- and High-Rise Buildings

As building height increases:

- Wind speed increases
- Turbulence intensifies
- Positive/negative pressure differences grow

Wind load influences:

- Local panel loads
- Global lateral loads acting on the main structure
- Diaphragm behaviour of floor slabs
- Bending and shear stresses in mullions

Load transfer under wind:

- Floors behave as diaphragms carrying shear
- Mullions transmit wind loads to slabs
- Panels transfer their loads to the frame

Therefore, the interface between the façade and the structure requires precise detailing.

2.4.1 Wind Load Performance of Curtain Wall Components

A robust curtain wall design requires:

- Laboratory testing
- Computational simulations (e.g., CFD analysis)
- Wind tunnel testing when appropriate

Above 200 m building height, wind tunnel testing becomes standard practice.

Wind loads follow this sequence:

1. The glass or panel surface receives the initial load.
2. The load transfers to stiffeners or perimeter supports.
3. Mullions and transoms receive this load.
4. Mullions pass the load to anchor brackets.
5. Anchors transfer the load to the building structure.

The façade engineer must ensure consistency between:

- Anchor design
- Mullion sizing
- Panel stiffness and strength
- Movement capacity (thermal–seismic–wind)
- Deflection limits

2.5 WIND LOAD PERFORMANCE OF CURTAIN WALL COMPONENTS

The wind performance of a curtain wall system is defined by the combined behaviour of its main components:

- **Framing system (mullions and transoms)**
- **Infill components (glass/panels)**
- **Anchors and fixings**

Wind load creates different types of deformation, strain, and displacement in each of these components. Therefore, each must be designed according to relevant performance criteria, industry guidelines, and European façade standards.

A detailed technical explanation of these behaviours follows in the next sections.

2.2.1 Frame Behaviour

Wind load causes **lateral deflection** in the curtain wall frame. If this deflection is not properly limited:

- The clearance between the glass panel and the frame may change,
- The glass bite may be reduced, creating a risk of glass disengagement,
- EPDM gaskets may compress excessively or tear,
- Gaps may open at stick and unitized joints.

For this reason, the **maximum permissible displacement** of framing members is a critical design parameter.

Deflection Limits in BS EN 13830:2015

According to the European standard, the maximum allowable **out-of-plane deflection** of a framing element is:

- $d \le \dfrac{L}{200}$ $d \le 200L$ for $L \le 3000 \text{ mm}$ $L \le 3000 \text{ mm}$ $L \le 3000\text{mm}$
- $d \le 5 \text{ mm} + \dfrac{L}{300}$ $d \le 5\text{mm} + 300L$ for $3000 \text{ mm} < L < 7500 \text{ mm}$ $3000 \text{ mm} < L < 7500\text{mm}$
- $d \le \dfrac{L}{250}$ $d \le 250L$ for $L \ge 7500 \text{ mm}$ $L \ge 7500 \text{ mm}$ $L \ge 7500\text{mm}$

where:

- L = span between supports of the member,
- d = measured deflection under the design wind load.

Infill elements (IGU, stone panels, composite panels, etc.) must be checked **independently** of the frame, with their own deflection criteria.

Exceeding these limits indicates that the system is **not capable** of carrying wind loads safely and that either the profile geometry, material thickness, or span must be revised.

2.2.2 Glass Behaviour

Wind pressure is one of the **most critical parameters** in selecting the type and thickness of glass. As building height increases, design wind pressure rises, and consequently glass thickness tends to increase, especially in high-rise projects.

A typical design sequence for glass is:

1. The **maximum design wind pressure** is calculated.
2. The corresponding **bending stress** in the glass is evaluated.
3. An appropriate glass build-up (tempered, laminated, IGU, etc.) and thickness is selected.

In many practical projects, the same glass thickness is used for all storeys for reasons of logistics, procurement, and cost control; differentiating glass thickness between lower and upper floors is often avoided unless performance demands it.

Possible Wind-Induced Problems in Glass

Under wind action, the following issues may arise:

- Breakage of toughened glass due to excessive tensile stress,
- Risk of delamination in laminated glass,
- Spacer deformation in insulating glass units (IGUs),
- Loss of contact between glass and frame due to excessive deflection,
- Loss of glass bite leading to the risk of drop-out.

Glass deflection is also important from a **user comfort** and **finish compatibility** perspective. Excessive bowing of large panes may cause visual distortion, reflected image distortion, and interaction problems with blinds, shading devices, or interior finishes.

Clift & Bonnheim (2013) emphasise that glass design should simultaneously consider:

- User comfort,
- Interaction with adjacent materials,
- Cumulative deformations,
- Loss of glass bite.

Glass resistance is determined as a function of glass type, load duration, bending strength, partial safety factors, and load distribution (uniform, non-uniform, localised).

2.2.3 Anchor Behaviour

The **anchor system** is responsible for safely transferring curtain wall loads to the primary structure. Accordingly, it must be capable of resisting:

- Lateral loads (mainly wind),
- Vertical loads (self-weight and additional permanent loads),
- Additional actions arising from seismic movements.

Fundamental Steps in Anchor Design

1. The **total weight** of the curtain wall system is determined.
2. Wind and seismic load combinations are defined.
3. Maximum forces at each anchor location are obtained using structural analysis software.
4. These forces are compared with the **design resistance** of the anchor system according to the relevant standard.
5. Concrete edge distances, embedment depths, and channel capacities are checked.

Hashemi (2018) groups the anchor design process under two main tasks:

- Determination of the forces at the connection point,
- Verification that the anchor channel and surrounding concrete can safely carry these forces.

Why Anchor Channels Are Often Preferred

Anchor channels offer significant advantages:

- They can accommodate lateral movements induced by wind,
- They provide installation tolerance and adjustability,
- They help reduce the risk of glass breakage due to misalignment,
- They allow for storey drift during earthquakes,
- They are well-suited to factory pre-assembly in unitized systems.

For these reasons, modern curtain wall designs frequently employ **channel-type anchors** wherever project conditions allow.

2.3 Codes and Standards Used in Curtain Wall Design

To correctly assess the role of wind load in curtain wall design, both **local** and **international** codes must be understood. The primary goal is to define the **minimum performance requirements** that ensure the curtain wall:

- Transfers wind loads safely,
- Does not suffer damage,
- Does not deform beyond acceptable limits,
- Protects the building and its occupants.

This section summarises how the main Turkish regulation, Eurocode 1, and U.S. standards approach wind load for curtain wall design.

2.3.1 İYBRY 2009 – Istanbul High-Rise Buildings Wind Code

In Turkey, one of the most frequently used references for wind load on tall buildings is the **İYBRY 2009**, issued by the Istanbul Metropolitan Municipality.

The code provides minimum values for designing:

- The primary load-bearing system, and
- All exterior cladding and non-structural components (including curtain walls).

Total Wind Speed – Equation (3.2)

The instantaneous wind speed at height zzz and time ttt is:

V(z,t)=Vm(z)+w(z,t)V(z,t) = V_m(z) + w(z,t)V(z,t)=Vm(z)+w(z,t)

where:

- Vm(z)V_m(z)Vm(z) = mean (quasi-static) wind speed,
- w(z,t)w(z,t)w(z,t) = dynamic component due to turbulence.

Mean Wind Speed – Equation (3.3)

$V_m(z) = C_e(z) \, C_t \, V_b$Vm(z)=Ce(z)CtVb

where:

- V_bVb = basic wind speed (25 m/s for Istanbul),
- $C_e(z)$Ce(z) = terrain roughness coefficient,
- C_tCt = topography factor.

Terrain Roughness – Equation (3.4)

Depending on terrain category:

$C_e(z) = k_r \ln \left(\frac{z}{z_0} \right)$Ce(z)=krln(z0z)

Table 3.1 in the code provides z_0z0 and $z_{\min}$zmin values for five terrain categories:

- Coastal regions,
- Lakes and flat open areas,
- Rural areas,
- Suburban/forested areas,
- Dense urban centres.

Topography Factor – Equation (3.5)

$C_t = 1.0 + 0.001 \, h$Ct=1.0+0.001h

where:

- hh = height above sea level.

Maximum Turbulence Speed – Equation (3.7)

$Q_w = k_r \, V_b$Qw=krVb

Maximum turbulence:

$W_{\max} = 3.5 \, Q_w$Wmax=3.5Qw

Maximum Wind Speed – Equation (3.10)

$|V(z,t)|_{\max} = V_m(z) + W_{\max}$|V(z,t)|max=Vm(z)+Wmax

Maximum Wind Pressure – Equation (3.11)

$q_p(z) = \frac{1}{2} \, \rho \, |V(z,t)|_{\max}^2$qp(z)=21ρ|V(z,t)|max2

where:

- $\rho = 1.25 \, \text{kg/m}^3$ρ=1.25kg/m3 (air density).

Dynamic vs. Static Approach

- Local **wind tunnel tests** are recommended for non-rectangular, irregular, or complex building geometries.
- For façade components, a pressure coefficient Cp=1.0C_p = 1.0Cp=1.0 is often adopted as a conservative value.

2.3.2 Eurocode 1 – Actions on Structures: Wind

Eurocode 1 (EN 1991-1-4) is the principal European standard used to determine a structure's behaviour under natural wind action. It is applicable not only to the main structure but also to:

- Curtain walls,
- Fixings and fasteners,
- Cladding and non-structural elements.

The code is generally considered directly applicable for buildings up to around **200 m** in height.

The wind action is decomposed into two components:

- **Mean component** → Vm(z)V_m(z)Vm(z)
- **Fluctuating component** → characterised by turbulence intensity Iv(z)I_v(z)Iv(z)

These are used to calculate both the **basic wind speed** and the **peak velocity pressure**.

2.3.2.1 Basic Wind Speed and Basic Velocity Pressure

The **basic wind speed** VbV_bVb is the reference wind speed at 10 m height above terrain category II. It is defined by:

$$V_b = C_{dir} \, C_{season} \, V_{b,0} \tag{3.14}$$

where:

- VbV_bVb = basic wind speed,
- Vb,0V_{b,0}Vb,0 = fundamental value given in the National Annex,
- CdirC_{dir}Cdir = directional factor (often taken as 1.0),
- CseasonC_{season}Cseason = seasonal factor (typically 1.0).

The **basic velocity pressure** is:

$$q_b = 0.5 \, \rho_{air} \, V_b^2 \tag{3.15}$$

where:

- qbq_bqb = basic velocity pressure (Pa),
- $\rho_{air} \approx 1.25 \, \text{kg/m}^3$.

2.3.2.2 Mean Wind Speed, Turbulence and Terrain Effects

To obtain the **peak velocity pressure**, the mean wind speed Vm(z)V_m(z)Vm(z) and turbulence intensity Iv(z)I_v(z)Iv(z) are required.

Eurocode expresses the peak velocity pressure as:

qp(z)=0.5 [1+7Iv(z)] ρair Vm(z)2(3.16)q_p(z) = 0.5 \, [1 + 7 I_v(z)] \, \rho_{air} \, V_m(z)^2 \tag{3.16}qp(z)=0.5[1+7Iv(z)]ρairVm(z)2(3.16)

The mean wind speed is given by:

Vm(z)=Cr(z) C0(z) Vb(3.17)V_m(z) = C_r(z) \, C_0(z) \, V_b \tag{3.17}Vm(z)=Cr(z)C0(z)Vb(3.17)

where:

- Cr(z)C_r(z)Cr(z) = roughness factor, accounting for terrain and height,
- C0(z)C_0(z)C0(z) = orography factor.

The roughness factor Cr(z)C_r(z)Cr(z) is defined as:

Cr(z)=krln⁡(zz0),zmin≤z≤zmax(3.18)C_r(z) = k_r \ln \left(\frac{z}{z_0} \right), \quad z_{\min} \le z \le z_{\max} \tag{3.18}Cr(z)=krln(z0z),zmin≤z≤zmax(3.18)

with:

- z0z_0z0 = roughness length (m),
- krk_rkr = terrain factor,
- zminz_{\min}zmin = minimum reference height,
- zmaxz_{\max}zmax = usually taken as 200 m.

The terrain factor is:

kr=0.19(z0z0,II)0.07(3.19)k_r = 0.19 \left(\frac{z_0}{z_{0,II}} \right)^{0.07} \tag{3.19}kr=0.19(z0,IIz0)0.07(3.19)

with z0,II=0.05 mz_{0,II} = 0.05 \, \text{m}z0,II=0.05m for terrain category II.

Eurocode defines **five terrain categories** (0 to IV), from open sea to dense urban cores, each with recommended z0z_0z0 and zminz_{\min}zmin values.

2.3.2.3 External and Internal Wind Pressures

The **external wind pressure** WeW_eWe is:

We=qp(ze) Cpe(3.20)W_e = q_p(z_e) \, C_{pe} \tag{3.20}We=qp(ze)Cpe(3.20)

where:

- qp(ze)q_p(z_e)qp(ze) = peak velocity pressure at reference height zez_eze,
- CpeC_{pe}Cpe = external pressure coefficient.

CpeC_{pe}Cpe depends on the loaded area AAA:

- For small elements → Cpe,1C_{pe,1}Cpe,1 (e.g. A≈1 m2A \approx 1 \, \text{m}^2A≈1m2)
- For larger elements → Cpe,10C_{pe,10}Cpe,10 (e.g. A≈10 m2A \approx 10 \, \text{m}^2A≈10m2)

For intermediate areas 1<A<10 m21 < A < 10 \, \text{m}^21<A<10m2, logarithmic interpolation is used:

Cpe=Cpe,1−(Cpe,1−Cpe,10) log⁡10(A)(3.21)C_{pe} = C_{pe,1} - (C_{pe,1} - C_{pe,10}) \, \log_{10}(A) \tag{3.21}Cpe=Cpe,1−(Cpe,1−Cpe,10)log10(A)(3.21)

The **internal pressure** WiW_iWi is:

Wi=qp(z) Cpi(3.22)W_i = q_p(z) \, C_{pi} \tag{3.22}Wi=qp(z)Cpi(3.22)

where:

- CpiC_{pi}Cpi = internal pressure coefficient, selected according to the size and distribution of openings.

EN 1991-1-4 requires that external and internal pressures be combined in the most **unfavourable** way, considering all relevant wind directions and opening configurations. For curtain wall design, these combinations govern:

- Glass thickness,
- Anchor sizing,
- Profile dimensions.

2.3.3 ASCE 7-10 – Minimum Design Loads for Buildings and Other Structures

ASCE 7-10 is another key standard, widely used in the United States and often referenced in international projects.

- Chapter 26: General wind load principles
- Chapter 30: Wind loads on **components and cladding**

Curtain walls fall under **“components and cladding”**, defined as:

Elements that receive wind load directly or from cladding and transfer these loads to the main wind force resisting system (MWFRS).

MWFRS (Main Wind Force Resisting System) is the part of the structure that provides overall stability and carries the global wind actions.

2.3.3.1 Basic Equation for Enclosed / Partially Enclosed Buildings

For enclosed and partially enclosed buildings, the **net design wind pressure** is:

P=q (GCp)−qi (GCpi)(3.23)P = q \, (G \, C_p) - q_i \, (G \, C_{pi}) \tag{3.23}P=q(GCp)−qi(GCpi)(3.23)

where:

- qqq = external velocity pressure,
- qiq_iqi = internal velocity pressure,
- GGG = gust factor,
- CpC_pCp = external pressure coefficient,
- CpiC_{pi}Cpi = internal pressure coefficient.

The velocity pressure is:

q=0.00256 Kz Kzt Kd V2(3.24)q = 0.00256 \, K_z \, K_{zt} \, K_d \, V^2 \tag{3.24}q=0.00256KzKztKd V2(3.24)

with:

- KzK_zKz = exposure and height coefficient,
- KztK_{zt}Kzt = topographic factor,
- KdK_dKd = wind directionality factor,
- VVV = basic wind speed (mph).

Typically:

- For windward walls, q=qzq = q_zq=qz at the relevant height,
- For other surfaces and internal pressure, q=qhq = q_hq=qh at mean roof height.

2.3.3.2 Risk Categories and Exposure Categories

ASCE 7-10 classifies buildings into **risk categories**:

- Category I: Low risk to human life in case of failure (e.g. agricultural buildings),
- Category II: Standard occupancy buildings (residential, typical commercial),
- Category III: Higher risk to human life (large assembly, high occupancy),
- Category IV: Essential facilities (hospitals, fire stations, etc.).

The basic wind speed VVV is taken from the **ASCE wind maps** for the relevant risk category. Then an **exposure category** (B, C, or D) is assigned based on the terrain in the upwind 45° sector.

Minimum net design pressure for components and cladding is typically:

Pmin≈0.77 kN/m2 (16 psf)P_{min} \approx 0.77 \, \text{kN/m}^2 \, (16 \, \text{psf})Pmin ≈0.77kN/m2(16psf)

and design pressures may not be taken below this value.

2.3.3.3 Coefficients: KdK_dKd, KztK_{zt}Kzt, KzK_zKz and Gust Factor

- **Directionality factor KdK_dKd:**
  Taken from Table 26.6-1 of ASCE 7-10. For example:
    - Buildings – MWFRS: 0.85
    - Components and cladding: 0.85
    - Towers, chimneys, free-standing walls: typically 0.85–0.95
- **Topographic factor KztK_{zt}Kzt:**
  Kzt=1.0K_{zt} = 1.0Kzt=1.0 for flat, unobstructed sites.
  For hills or escarpments, it is computed from Figure 26.8.
- **Velocity pressure coefficient KzK_zKz:**

Kz=2.01(zzg)2/α(15 ft<z<zg)(3.25)K_z = 2.01 \left(\frac{z}{z_g} \right)^{2/\alpha} \quad (15 \, \text{ft} < z < z_g) \tag{3.25}Kz=2.01(zgz)2/α(15ft<z<zg)(3.25)

where:

- zgz_gzg = upper limit of the wind profile for the given exposure,
- α\alphaα = exposure-dependent exponent.

For heights below 15 ft, KzK_zKz is taken as the value at 15 ft.

- **Gust factor GGG:**
  For typical rigid buildings, G=0.85G = 0.85G=0.85 is commonly used.

2.3.3.4 Internal/External Pressure Coefficients and Final Design Pressure

- **Internal pressure coefficient GCpiG C_{pi}GCpi:**
  Selected from Table 26.11-1 based on building type (open, partially open, enclosed).
  For enclosed buildings, typical values are around ±0.18\pm 0.18±0.18.
- **External pressure coefficient GCpG C_pGCp:**
  Taken from the diagrams in Chapters 27 and 30 (e.g. Figs. 27.4-1, 27.4-3, 30.4-1), depending on building geometry and surface zone.

Finally, for components and cladding (including curtain walls), the **design wind pressure** is:

P=qh [(GCp)−(GCpi)](3.26)P = q_h \, \big[(G C_p) - (G C_{pi})\big] \tag{3.26}P=qh[(GCp)−(GCpi)](3.26)

where:

- qhq_hqh = velocity pressure at mean roof height,
- GCpG C_pGCp = external pressure coefficient,
- GCpiG C_{pi}GCpi = internal pressure coefficient.

The most **unfavourable combination** of positive and negative internal/external pressures is used to size curtain wall profiles, glass thicknesses, and anchor systems.

2.10.4 Comparison of Wind Standards

The increasing standardisation of international wind codes has made it essential to understand the differences between them, particularly for curtain wall design. Among the most commonly referenced documents are the **IYBRY** (Istanbul High-Rise Buildings Wind Code), **Eurocode 1 (EN 1991-1-4)** and **ASCE 7-10**. Although their overall objectives are similar, there are important methodological differences.

The main distinctions can be summarised as follows:

- **Definition of basic wind speed and averaging time**
    - In **ASCE 7-10**, the basic wind speed is defined as a **3-second gust**.
    - In **Eurocode 1** and **IYBRY**, the basic wind speed is based on a **10-minute mean** wind velocity.

This difference in averaging time leads to different values of VbV_bVb for the *same region*, depending on which standard is used.

- **Reference height and response time**

The gust effect factor, reference height and structural response time depend not only on the standard itself but also on the building type and dynamic characteristics considered within each code.

- **Wind speed profile**
    - **Eurocode 1** and **IYBRY** primarily use a **logarithmic law** to define the vertical wind speed profile.
    - **ASCE 7-10** adopts a **power-law** profile.

As a result, the velocity pressures calculated at the same height may differ between standards.

- **Method of obtaining basic wind speed**
    - In **Eurocode**, VbV_bVb is typically provided in the National Annex, often with direction and season factors CdirC_{dir}Cdir and CseasonC_{season}Cseason taken as 1.0.
    - **IYBRY** specifies Vb=25 m/sV_b = 25 \, \text{m/s}Vb=25m/s as the basic wind speed for Istanbul.
    - **ASCE 7-10** uses regional **wind maps**, from which the basic speed is read directly (in mph).
- **Gust effects / structural factors**
    - In **ASCE 7-10**, the gust effect factor GGG includes a formulation that incorporates a **0.925 factor** to ensure continuity with previous editions.
    - In **IYBRY**, a similar concept appears as a “tail factor”.
    - In **Eurocode**, the same effect is represented through structural factors such as Cs·CdC_s \cdot C_dCs·Cd.
- **Peak factor**

The peak factor, defined as the ratio of the maximum fluctuating response to its standard deviation:

- In **ASCE**, is typically taken as a constant in the range **3–4**.
- In **Eurocode**, a more detailed statistical description is used via a factor denoted gRg_RgR.

- **Internal and external pressure coefficients**

All three standards define external pressure coefficients (Cpe/Cp) for windward and leeward surfaces, but their treatment of **internal pressure** differs:

- **ASCE 7-10**: Provides ranges for CpiC_{pi}Cpi in Table 26.11-1 depending on building type (enclosed, partially enclosed, open).
- **Eurocode 1**: Uses an equation-based approach and selects CpiC_{pi}Cpi according to the proportion and distribution of openings.
- **IYBRY**: For non-structural elements such as curtain walls, recommends taking the external pressure coefficient as **1.0**, and computing the internal coefficient based on opening areas via two relationships:
  - If the opening area on one façade is at least twice the sum of openings on all other façades:

Cpi=0.75 CpeC_{pi} = 0.75\, C_{pe}Cpi=0.75Cpe

  - If the opening area on one façade is at least three times the sum of openings on all other façades:

Cpi=0.90 CpeC_{pi} = 0.90\, C_{pe}Cpi=0.90Cpe

- **Across-wind and torsional effects**

ASCE, **Eurocode** and **IYBRY** all acknowledge across-wind and torsional effects and typically use a **partial loading** approach to capture them. ASCE 7-10, in Commentary C26.9, also presents alternative methods for modelling these effects.

- **Acceleration and comfort criteria**

Comfort criteria related to across-wind and torsional accelerations are not addressed with the same level of detail in all standards; in some, they are treated only in a limited or indirect manner.

- **Combination of peak responses**

For combining along-wind, across-wind and torsional peak responses, some codes provide explicit combination rules. For example, **ASCE 7** includes Figure 27.4-8, which proposes a graphical method for combining these effects.

These differences mean that, for the **same building**, curtain wall systems designed to different standards may require **different profile sizes, glass thicknesses and anchor dimensions**. In international projects, it is therefore crucial to define at the very beginning of the design process **which code will be regarded as the primary reference**.

2.11 Experimental and Numerical Methods for Wind Load Assessment

In façade and curtain wall engineering, determining wind loads solely from theoretical formulae is not always sufficient. In particular, for complex geometries, tall buildings and projects subject to strong environmental effects, design verification is increasingly supported by:

- Laboratory tests,
- Computational Fluid Dynamics (CFD) simulations,
- Wind tunnel experiments.

The choice of method depends on:

- Building height,
- Geometric complexity,
- Type of façade system,
- Criticality and budget of the project.

2.11.1 Wind Resistance Tests

Wind resistance testing is used to evaluate the behaviour of curtain wall systems—both fixed and operable units—under positive and negative design wind pressures. The principal reference is **BS EN 12179:2000 – Curtain Walling – Resistance to Wind Load – Test Method**.

Before testing:

- At least **three displacement transducers** are installed along the main vertical mullion (typically at mid-height and quarter points).
- These sensors record frame deflection **before and after** load application.

The permissible maximum forward deflection is:

- $d \le \dfrac{L}{200}$ for $L \le 3000 \text{ mm}$
- $d \le 5 \text{ mm} + \dfrac{L}{300}$ for $3000 \text{ mm} < L < 7500 \text{ mm}$
- $d \le \dfrac{L}{250}$ for $L \ge 7500 \text{ mm}$

where LLL is the distance between supports of the tested façade element.

According to **BS EN 13116:2004**, at least **95%** of the measured deflection should recover within **1 hour** after unloading; the deformation should be essentially **elastic**, with no significant residual deflection.

A simplified outline of the test procedure is:

1. Positive and negative loads equal to **50% of the design value** are applied for **1–3 seconds**.
2. Then, loads corresponding to **25%, 50%, 75% and 100% of the design load** are applied sequentially, each for approximately **15 seconds**, first in the positive and then in the negative direction.
3. At each stage, façade deflections are recorded by the sensors.

4. Glass breakage, profile distortion or twisting, gasket dislocation and similar damage are closely observed and documented.

To assess safety margins, an additional **overload test** is usually performed:

- A load equal to **150% of the design pressure** is applied for 15 seconds.
- Deflections are typically not recorded for this step, but the system is expected not to collapse; glass should not fall out and primary components should not suffer irreversible failure.
- If glass breaks, the cause is analysed, the pane is replaced and testing may continue.

These tests provide valuable feedback to the designer regarding the **true safety level** of the system under wind action.

2.11.2 CFD (Computational Fluid Dynamics) Simulations

Computational Fluid Dynamics (CFD) is a numerical tool that enables three-dimensional analysis of:

- Wind flow around buildings,
- Pressure distributions on façades,
- Turbulence structures in the surrounding flow field.

With CFD, one can:

- Model 2D or 3D wind fields around a building,
- Estimate mean external pressure coefficients CpeC_{pe}Cpe,
- Visualise wind velocity, pressure and temperature fields using contour plots and streamlines.

However:

- A realistic CFD simulation requires careful selection of mesh type and density, turbulence model, boundary conditions and time-stepping strategy.
- This increases computational effort and makes fully detailed analyses challenging in the early design stages (Castro, 2015).

Consequently, CFD is most commonly used:

- For **low- and mid-rise** buildings,
- With geometries that are not extremely complex,

as a **complementary** check to code-based calculations. For very tall or highly irregular buildings, CFD alone is not considered sufficient and is usually coupled with **wind tunnel testing**.

Typical applications of CFD in curtain wall design include:

- Comparing pressure distributions on different façade surfaces,
- Identifying regions where maximum suction or pressure occurs,
- Providing preliminary estimates of local loads near corners, recesses, projections and canopies.

2.11.3 Wind Tunnel Tests

According to **ASCE/SEI 49-12**, wind tunnel testing comprises:

"Experimental methods used to predict wind-induced loads and responses of structures, structural components and cladding under a range of wind conditions."

For buildings of standard geometry and limited height:

- Local codes,
- Eurocode / IYBRY / ASCE calculations, and
- CFD analyses (if needed)

are often considered sufficient.

However, wind tunnel testing becomes almost **mandatory** when the building is:

- Tall (e.g. 200 m and above),
- Geometrically complex,
- Located in strong wind corridors,
- Surrounded by other tall structures that significantly alter the wind field.

IYBRY explicitly requires wind tunnel tests for buildings taller than **200 m**, and recommends them for lower yet highly complex buildings.

Summary of the Wind Tunnel Process

1. The architectural massing is broadly defined (volume and proportions).
2. A physical scale model of the building and its surroundings (typically 1:200–1:500) is fabricated.
3. The model is placed in a wind tunnel configured to reproduce the relevant atmospheric boundary layer.
4. Surrounding buildings within at least **300–500 m** radius are included, since neighbouring structures strongly influence the wind environment.
5. For multiple wind directions, speeds and turbulence intensities, local pressure time histories on the façade are recorded using pressure taps.
6. From these measurements, engineers derive:
    - Mean pressures,
    - Peak pressures,
    - Suction values,
    - Across-wind and torsional effects,
    - Structural response and acceleration levels.

The resulting data are:

- Compared with code-based predictions,
- Used to identify areas where local peak suctions exceed standard values,
- Employed to refine glass thicknesses, profile sizes and anchor types if necessary.

Recent studies indicate that when **CFD and wind tunnel results** are used together, the wind behaviour of façades—especially on tall buildings—can be predicted more realistically. In this context, CFD often supports the **early design phase**, while wind tunnel testing serves as a **final validation tool**.

Evaluation and Conclusions

This chapter has demonstrated why wind load must be treated as a **central design parameter** in curtain wall engineering, from both meteorological and structural perspectives.

First, the general wind regime of Turkey, and specifically the prevailing winds in Istanbul, has been summarised. On the European side of the city, dominant directions lie between NNW–N–NNE; on the Asian side, prevailing winds tend to rotate between **north-eastern and north-western sectors**, which is critical for façade orientation and detailing.

Next, the principal wind codes and standards used in Turkey and internationally for curtain wall and façade design have been reviewed. For buildings up to 200 m in height, IYBRY assumes a basic wind speed of **25 m/s** for Istanbul and defines:

- Mean wind speed,
- Dynamic (turbulent) wind component,
- Maximum wind speed,
- Maximum wind pressure,

using an air density of approximately ρ≈1.25 kg/m3\rho \approx 1.25 \, \text{kg/m}^3ρ≈1.25kg/m3. Wind actions, influence coefficients and impact factors are combined, and the maximum façade displacement is often evaluated using an **equivalent static load** approach.

Eurocode 1 (EN 1991-1-4), on the other hand, provides a systematic framework for evaluating external and internal pressures via:

- External pressure coefficients CpeC_{pe}Cpe,
- Internal pressure coefficients CpiC_{pi}Cpi,
- Terrain roughness and height effects,
- Turbulence intensity.

Thus, wind load is treated not as a single “kN/m2\text{kN/m}^2kN/m2” value but as a **pressure field** acting on the façade, combined with internal pressure regimes.

Building on these theoretical and code-based approaches, the chapter then discussed the experimental and numerical tools used to refine wind load assessment:

- **CFD simulations**, which provide three-dimensional insight into flow and pressure patterns around the building,
- **Wind tunnel tests**, which capture local peak suctions/pressures, torsional and across-wind responses for tall and complex structures,
- **Wind resistance tests**, which verify at full scale the deflection, breakage and recovery behaviour of curtain wall modules.

Experience from both literature and practice shows that when only standard code values are used, wind tunnel results often reveal **higher local peak pressures and suctions** than those predicted by simplified methods. Various studies suggest that combining CFD and wind tunnel data yields more realistic and safer estimates of wind loads on façades, especially for tall buildings and irregular geometries.

If these tools are neglected, or if design strictly adheres only to theoretical minima, the following types of damage may occur under wind action:

- Cracking, blow-out or falling of glass panels,
- Twisting, excessive deflection or permanent deformation of aluminium/steel framing,
- Loosening, failure or fatigue damage in anchors and connections,
- Progressive degradation of gaskets, sealants and weatherproofing components under repeated loading.

In summary, within curtain wall design, wind load should be regarded not as:

1. A simple catalogue value, but as
2. A design action that must be interpreted through a combination of codes, experiments and simulations, and
3. A key factor with direct impact on façade safety, occupant comfort and long-term maintenance cost.

2.13 Comparative Analysis of Wind Load Effects on Curtain Wall Performance

Although curtain walls form the **outer skin** of a building, they are classified as **non-load-bearing** elements. Nevertheless, under wind loading their behaviour has a decisive influence on **structural safety**, **serviceability** and **long-term durability**. It is therefore essential to analyse wind effects on the façade in a **component-based** and comparative manner.

The impact of wind load on curtain walls can be grouped into three principal categories:

1. **Local pressure effects** (panel and glass surfaces),
2. **Global load transfer** (mullion–transom behaviour),
3. **Load transfer paths at connections and anchors**.

This section systematically examines the behaviour of each curtain wall component under wind action.

2.13.1 Distinction Between Local and Global Pressures

When wind acts on a curtain wall surface, the resulting load can be decomposed into **local** and **global** components.

Local Pressures (Panel Pressure)

- These are the pressures and suctions acting **directly on the glass or opaque panel surfaces**.
- Short-duration peak pressures arising from turbulent flow can be significantly higher than the corresponding global actions.
- They are typically calculated using the external pressure coefficient CpeC_{pe}Cpe defined in **ASCE 7-10** or **EN 1991-1-4**.

The critical implications of local pressures include:

- Selection of **glass thickness**,
- Internal pressure equalisation of IGUs,
- Deformation risks in spandrel panels,
- Risk of disengagement or pull-out of panel fasteners.

Global Pressures (Overall Structural Load)

- Global wind loads govern the **bending, shear and torsion behaviour** of mullions and transoms under the combined effect of panel loads.
- Since these loads control overall **frame deflection**, they are directly related to perceived movements during service.

Global actions:

- Define the **moment and shear diagrams** of mullions,
- Challenge the horizontal and vertical load capacity of anchor systems,
- Form the basis for checking deflection limits such as L/200L/200L/200, L/250L/250L/250 and similar criteria.

In subsequent sections, these local and global effects will be related to individual components—glass, framing, anchors and connections—to provide a coherent picture of curtain wall performance under wind loading.

2.13.2 Deformation Curves of Mullions

The deformation behaviour of the framing system forms the backbone of the curtain wall response under wind loading. Mullions and transoms, while transferring loads from the infill panels to the anchors, exhibit three fundamental deformation modes:

1. Flexural deflection,
2. Shear deformation,
3. Rotations at the points of connection (fixity rotation).

This behaviour concerns the entire load-transfer chain, from the glass surface to the primary structure.

The shape of the deformation curve is governed by several key parameters:

- Torsional and flexural stiffness of the profile (values of IyI_yIy, IxI_xIx),
- Span length LLL,
- Wind pressure qqq,
- Panel dimensions,
- Support and boundary conditions at anchor locations (fixed, pinned, sliding, etc.).

In modern curtain wall design, many serviceability problems arise **not** because the glass reaches its ultimate capacity, but because **mullion deflection** becomes excessive **before** the glass design load is reached.

For this reason, mullion behaviour under wind load has a **direct impact on glass safety**, bite retention and the long-term performance of gaskets and sealants.

2.13.3 Peak Pressure Zones on Glass

The distribution of wind pressure on a glass surface is not uniform. At corners, along parapet lines and in edge regions:

- Turbulence intensity increases,
- Rotational flow structures (eddies) occur,
- External pressure coefficients CpeC_{pe}Cpe exhibit sudden peak values.

Therefore, in glass design, particular attention must be paid to:

- Higher safety factors for edge and corner zones,
- Internal pressure equalisation of insulating glass units (IGUs),
- Control of loss of bite at the glass–frame interface,
- Noise, vibration and resonance problems induced by fluctuating suction.

On tall buildings in the order of **200–300 m**, peak negative pressures measured in wind tunnel tests can exceed the values suggested in codes by **30–50%**.

This clearly underlines the importance of wind tunnel testing for projects with high façades and sensitive glass design.

2.13.4 Behaviour of Infill (Spandrel) Panels

Unlike vision areas, the **spandrel zone** is typically a multi-layered construction, consisting of:

- Aluminium or steel facing panels,
- Thermal insulation packages,

- Back pans,
- Fire barriers,
- Vapour control or balancing layers.

Consequently, its response to wind loading differs significantly from that of monolithic or insulating glass.

Representative risk conditions for spandrel panels include:

1. **Oil-canning** (visible surface waviness or dish-shaped deformations),
2. Panel vibration and resonance under cyclic wind action,
3. Surface delamination or debonding in adhesive systems,
4. Local overstressing at anchorage and fixing points.

Although spandrel elements are often **stiffer** than glass, short-duration peak suctions generated by local turbulence may still cause **panel separation** or **fastener failure** if the system is not correctly detailed.

2.13.5 Load–Transfer Curves of Anchor Points

The anchorage system represents the physical interface between the curtain wall and the primary structure; it is the **critical node** in the overall load-transfer chain.

Loads acting on anchors include:

- Horizontal loads due to wind pressure,
- Vertical loads due to the self-weight (dead load) of the curtain wall,
- Movements caused by thermal expansion and contraction,
- Inter-storey drift and relative lateral displacement,
- Construction and installation tolerances.

Anchor performance is primarily characterised by three parameters:

1. **Load–displacement curve** (stiffness and residual deformation),
2. **Rotational capacity** at the connection,
3. Behaviour under **cyclic and repeated loading**.

In both European and American design approaches, a common philosophy applies:

- Each anchor point must be checked against **local peak pressures**, rather than only average global loads.
- Global actions are distributed among mullions and transoms according to their relative stiffness.
- The rotations induced in the anchors by frame deformation must be **explicitly modelled**, as they influence both serviceability and ultimate capacity.

2.14 Safety Factors and Design Philosophy for Wind Loads

In curtain wall systems, wind load is the **most decisive** design action. Glass, mullions, transoms, anchor connections and all infill elements are evaluated under various **load combinations** and **safety factors**. According to modern standards, the objective of wind design is not only to prevent **element failure** but also to ensure:

- Adequate serviceability performance,
- Compliance with deflection limits,
- Sufficient fatigue resistance under repeated loading,
- Long-term safety of connections and fixings.

Therefore, wind design is not limited to determining pressure values; it also encompasses:

- How loads are transmitted through the curtain wall components,
- The geometric and structural behaviour under load,
- Permissible deformation limits,
- Loss of bite in the glass–frame interface,
- Rotational capacity of anchor points.

All of these aspects form an integral part of a comprehensive design process.

2.14.1 Safety Factors Used in Design

International standards (EN 1991-1-4, EN 13830, ASCE 7-10, IYBRY 2009) propose different safety factors and philosophies for wind design. For curtain walls, these can be grouped under three main headings:

(a) Load Factor (γF\gamma_FγF)

To account for the inherent variability and randomness of wind, a factor is applied to the design load:

- In **Eurocode**, the typical value is γW=1.5\gamma_W = 1.5γW=1.5.
- In **ASCE**, explicit load factors are embedded in ASD/LRFD load combinations rather than expressed as a single γW\gamma_WγW.
- In **IYBRY**, a specific γ\gammaγ value is not always stated; however, the calculated wind loads already include an implicit safety margin.

(b) Material Factor (γM\gamma_MγM)

Because safety of non-structural materials such as glass, aluminium and steel anchors is critical, Eurocode, ASCE and EN 13830 define distinct material safety factors:

- **Glass**
    - As a brittle material, glass is assigned relatively high safety factors.

    - EN 16612 defines design strengths depending on glass type.
    - Typical γM\gamma_MγM values range between **1.6 and 2.0**.
- **Aluminium profiles**
    - Common values lie in the range γM≈1.1–1.2\gamma_M \approx 1.1–1.2γM≈1.1–1.2.
- **Steel anchors**
    - Often taken as γM=1.0–1.1\gamma_M = 1.0–1.1γM=1.0–1.1, since steel is a ductile and high-strength material with well-established design rules.

(c) Serviceability Limit State (SLS) Factors

These factors do not aim to prevent failure, but to restrict **deflections** and **perceived movements** within acceptable limits:

- Typical deflection limits:
    - For glass: between **L/90 and L/120**,
    - For mullions: **L/200 or L/250**,
    - For spandrel elements: around **L/175**.

At the SLS, the load factor on wind is usually taken as **1.0**.

This is crucial in high-rise buildings, where excessive sway or visual movement under wind may lead to occupant discomfort and loss of glass bite.

2.14.2 Design Philosophy: Extended Load Path Approach

The most robust curtain wall design philosophy is based on meticulously **tracing the load path**. This approach, widely adopted by international façade consultants and recognised by EN 13830, can be summarised as follows:

Wind load on a curtain wall proceeds through the system in this order:

1. Wind acts on the **glass or infill panel**.
2. The glass transfers the load through its **bite area** to the supporting profiles.
3. Mullions and transoms carry the load along the storey height or span.
4. The mullion ends transmit the load to the **anchors**.
5. Anchors transfer the load to the **primary structure** (reinforced concrete or steel).

If at any point along this path there is:

- Insufficient stiffness,
- Inadequate connection detailing,
- Loss of glass bite,
- Excessive deformation,

the system may fail, even if all individual components meet their nominal strength.

Modern design therefore considers not only static strength, but also **dynamic response**, **material fatigue**, **connection rotation** and overall **service performance** as part of the wind design.

2.14.3 Wind Load Combinations

Wind load is never evaluated in isolation. International standards typically prescribe three principal combination types:

(1) Ultimate Limit State (ULS – Strength Design)

This combination checks the resistance of elements against **failure**.

Example Eurocode combination:

1.35G+1.5Q+1.5W1.35G + 1.5Q + 1.5W1.35G+1.5Q+1.5W

Example ASCE LRFD combination:

1.2D+1.6W1.2D + 1.6W1.2D+1.6W

In this stage, the designer checks:

- Profile strength,
- Anchor capacity,
- Glass breakage resistance.

(2) Serviceability Limit State (SLS – In-Use Performance)

Here, the focus is not on collapse but on **acceptable** levels of deformation.

Typical Eurocode SLS combination:

G+Q+WG + Q + WG+Q+W

At SLS, the following are verified:

- Mullion deflection (e.g. L/200, L/250),
- Glass deflection,
- Loss of glass bite,
- Overall curtain wall sway and service behaviour.

(3) Fatigue Analysis (High-Rise Structures)

Because wind is a **repeated** action, fatigue becomes important in buildings above approximately **150–200 m**:

- Anchor bolts,

- Connection zones of aluminium profiles,
- Glass–silicone joints

may experience long-term deformation or damage under cyclic loading.

Combined **CFD** and **wind tunnel** results are often used to support fatigue assessments.

2.14.4 Key Parameters in Load Distribution

The main variables that directly influence wind load calculations and their application to curtain wall design include:

1. Terrain roughness category,
2. Building height,
3. Enhanced CpeC_{pe}Cpe values for corner and edge regions,
4. Building geometry and plan shape,
5. Wind direction and local wind statistics,
6. Turbulence intensity IvI_vIv,
7. Peak factor for wind response,
8. Dynamic amplification factors.

Wind tunnel studies, in particular, demonstrate that CpeC_{pe}Cpe distributions on tall buildings can deviate significantly from those assumed in simplified code diagrams.

2.14.5 Summary of the Design Approach

In summary, wind load assessment for curtain wall design follows these steps:

1. Determination of basic wind speed from local codes or Eurocode/ASCE.
2. Calculation of basic wind pressure.
3. Evaluation of **local panel pressures**.
4. Analysis of global loads on mullions and transoms.
5. Verification of deflection limits.
6. Calculation of anchor forces.
7. Validation of results using wind tunnel tests and/or CFD as necessary.
8. Checks for both **serviceability** and **ultimate** limit states.
9. Glass breakage analysis and verification of bite retention.
10. Application of appropriate safety factors to the entire system.

In contemporary high-rise building design, this workflow is not optional but **essential**.

2.15 Influence of Wind Loads on Curtain Wall Glass Design

Glass is both the **visual** and **functional** centre of modern curtain wall systems. However, glass design in façades is far more than a question of optical quality: understanding how glass behaves under wind loading is one of the most critical stages of the design process.

Because glass is a **brittle material**, wind load directly governs its:

- Safety,
- Performance,
- Long-term durability.

Accordingly, glass design under wind action is examined along three main axes:

1. Resistance to **pressure and suction** loads,
2. Permissible **deflection limits** of the glass,
3. **Bite retention** and stability of the pane within the frame.

This section discusses the behaviour of glass under wind load in a systematic manner.

2.15.1 Fundamental Parameters Governing Glass Thickness

Glass thickness is often associated with mechanical capacity, yet in curtain walls the design is **not** based solely on ultimate strength. The following parameters must be considered simultaneously:

(a) Wind Pressure qpq_pqp

- Positive pressure on the windward face,
- Negative pressure (suction) on the leeward face.

Negative pressure is generally more critical for glass design, particularly in high-rise buildings, as it increases the risk of panel blow-out and tensile stress failure.

(b) Panel Area and Aspect Ratio

As the panel area increases:

- Bending moments in the central zone of the glass rise,
- Deflections grow,
- Required thickness and stiffness increase.

Panels larger than approximately **1.5 m × 3.0 m** typically demand significantly higher rigidity and careful checks of both strength and serviceability.

(c) Support Conditions (Four-Edge, Two-Edge, Point-Supported)

- **Four-edge supported** glass generally offers the safest and stiffest configuration.

- In **two-edge supported** systems, bending stresses increase dramatically and must be carefully checked.
- In **spider or point-supported systems**, the local effect at fixing points makes glass design much more critical and sensitive to detailing.

(d) Glass Type (Tempered, Heat-Treated, Laminated, IGU)

Each glass type has:

- Different characteristic strengths,
- Different failure modes,
- Different design rules and safety factors.

Laminated glass, for example, may provide post-breakage integrity but must be designed with appropriate interlayer properties and load duration factors.

(e) Load Duration

Wind is classified as a **short-duration** load. Accordingly, the **short-term** characteristic strength of glass is used in design, rather than long-term values which would apply to sustained loads.

2.15.2 Glass Deflection Under Wind

The most visible manifestation of wind action on glass is the **deformed surface shape** and **mid-pane deflection**. Deflection criteria are therefore central to glass design.

Glass deflection is limited for several reasons:

1. To prevent the glass from moving out of the **bite zone** within the frame,
2. To avoid **friction and contact** between glass and metal profiles that may cause edge damage or breakage,
3. To preserve the **hermetic seal** of insulating glass units (IGUs),
4. To prevent visually disturbing **optical distortion** and waviness,
5. To reduce **fatigue** effects under repeated wind loading.

Typical serviceability deflection criteria are:

- **Monolithic glass**: between L/90L/90L/90 and L/120L/120L/120,
- **Insulating glass units (IGUs)**: between L/175L/175L/175 and L/240L/240L/240,
- **Maximum central deflection**: often limited to approximately **25 mm**.

These values are generally derived with reference to **Eurocode**, **ASTM E1300** and **EN 16612**, and may be tightened for high-rise applications or visually critical façades.

2.15.3 Glass Bite and the Effect of Wind on Bite Loss

The **bite** is the effective engagement length of the glass within the supporting frame, providing a passive safety margin against movement and dislodgement.

- Typical bite values range between **12–15 mm**,
- In high-wind regions, the bite may be increased up to **18 mm**.

Under wind, the pane moves forwards and backwards, causing **relative slip** within the bite zone. This sliding can lead to a number of risks:

- The glass may **walk out of the gasket** or setting blocks,
- Excessive stress may accumulate along the **glass edge**,
- For laminated glass, the **interlayer (e.g. PVB)** may become exposed at the edge,
- In IGUs, the **edge seal** and spacer system may be damaged or overstressed.

For this reason, design guidelines typically require that glass deflection does **not exceed about 70%** of the available bite.

For taller panels and high-rise façades, a **bite loss analysis** is mandatory, combining frame deflection, glass deflection and movement tolerances into a single check.

2.15.4 Specific Effects of Wind Pressure on IGU (Insulating Glass) Units

Insulating glass units (IGUs), consisting of two or three panes separated by gas-filled cavities, react differently to wind loads compared to monolithic glass.

The main IGU behaviours under wind are:

1. **Barometric expansion**
   The gas volume within the cavity **expands or contracts** under changing external pressure, increasing mid-pane deflection.
2. **Differential pressure effects**
   At higher altitudes, the **internal gas pressure** may become significantly different from the external pressure, causing the unit to bow (convex or concave).
3. **Non-uniform deflection**
   The outer pane generally exhibits **larger deflections** than the inner pane, resulting in complex stress distributions across the unit.

For IGUs used in high-rise façades, it is therefore common practice to adopt:

- **Tempered glass** on the exterior pane,
- **Heat-strengthened (HS)** glass on the interior pane,
- **Warm-edge spacers** to reduce thermal stresses and edge losses,
- **Argon or helium** gas fill to optimise thermal and mechanical performance,
- Cavity widths in the order of **16–20 mm**.

These measures aim to balance structural safety, durability of the edge seal, and thermal/visual performance under combined wind and climate actions.

2.15.5 Resonance and Dynamic Effects

Wind loading is not purely static; it exhibits **time-dependent**, fluctuating components that can excite dynamic behaviour in glass panels.

Factors increasing the risk of resonance in glass include:

- Large panel sizes,
- Thin glass or under-reinforced IGUs,
- Long-duration, repeated wind events,
- High-frequency turbulence,
- **Spider** and other point-supported systems with localised stiffness.

Under resonance conditions, the glass surface may display:

- Pronounced **wave patterns**,
- High-frequency **vibrations**,
- Increased **gasket wear**,
- **Fatigue** in silicone joints and edge seals.

CFD simulations and **wind tunnel tests** can be used to assess the likelihood of resonance and to identify critical wind speeds and directions, especially in tall buildings or complex geometries.

2.15.6 Risk Analysis of Glass Breakage

Glass failure in curtain walls can occur due to the exceedance of design wind pressures, but in practice, failures are more frequently associated with **edge stresses** and **local defects**.

Common causes of glass breakage include:

- Inadequate or poor-quality **edge finishing**,
- High **localised stresses** from point supports or hard contact points,
- Insufficient **bite** or uneven support,
- Installation and handling defects,
- **Thermal shock** due to localised heating or shading,
- Underestimation of **peak wind loads** and suction pressures.

To minimise breakage risk, it is essential to ensure:

- Appropriate use of **fully tempered** or **heat-strengthened** glass where required,
- Correct **bite depth** and uniform support conditions,
- Proper **spacer thickness** and edge detailing in IGUs,
- Reliable determination of **design wind loads**, including peak effects and local suction zones.

2.15.7 Final Design Stage: SLS and ULS Assessment of Glass Performance

Glass design is completed only when both **serviceability** and **ultimate** limit states are satisfied simultaneously.

Serviceability Limit State (SLS) checks include:

- Compliance with deflection limits,
- Control of **bite loss**,
- Verification of **IGU tightness** and edge seal performance,
- Evaluation of potential **resonance** and perceptible vibrations.

Ultimate Limit State (ULS) checks include:

- Maximum allowable stresses in the glass,
- Verification of **breakage resistance** under factored wind loads,
- Adequate safety factors according to the relevant standard.

The final glass specification is the solution that **meets both SLS and ULS criteria**, often with additional project-specific requirements regarding post-breakage behaviour, fall protection and human safety.

2.16 Wind-Based Structural Design of Aluminium Profiles

In curtain wall systems, aluminium profiles form the **primary load-carrying skeleton** that receives the wind load from the infill elements and transfers it safely to the frame–anchor system. Consequently, accurate assessment of:

- Stresses,
- Deflections,
- Rotations and connection forces

under wind load is a critical engineering requirement.

Aluminium has become the dominant material for façades due to its **low weight**, **formability** and **corrosion resistance**. However, its **modulus of elasticity** is roughly **one-third** that of steel. As a result, aluminium members exhibit larger deflections under the same load. In curtain wall design, therefore, it is often **serviceability (deflection)** rather than **ultimate strength** that governs profile selection.

2.16.1 Fundamental Concepts: Wind Load Effects on Profiles

Understanding profile design requires familiarity with three basic structural concepts:

(a) Bending Moment

The wind pressure acting on the glass is transferred as a **distributed load qqq** to the mullions and transoms. This load produces:

- Bending moment M(x)M(x)M(x),
- Shear force V(x)V(x)V(x)

along the member. Increasing the profile depth hhh substantially increases the bending capacity.

(b) Moment of Inertia IxI_xIx

The **moment of inertia** reflects the geometric stiffness of the profile. A higher moment of inertia leads to lower deflections:

- A tall mullion profile ⇒ high IxI_xIx ⇒ small deflection.

Thus, a 125 mm deep mullion can exhibit **several times less deflection** than a 50 mm deep profile under the same load.

(c) Modulus of Elasticity EEE

The modulus of elasticity of aluminium is approximately **70 GPa**, whereas steel is about **210 GPa**.

Therefore, curtain wall profiles are typically designed as:

- **Deep**,
- **Box-shaped**,
- Often with **internal reinforcement** or steel inserts,

to compensate for aluminium's lower stiffness.

2.16.2 Structural Logic of Mullion–Transom Systems

The load-carrying scheme of a curtain wall can be summarised as:

1. The **glass** receives the wind load.
2. The load is transferred via **gaskets and pressure plates** to the mullions and transoms.
3. The **mullion** carries the load vertically to two or more **anchor points**.
4. Anchors transfer the load to the **reinforced concrete slab** or steel beam.

The mullion is typically the most critical member because:

- It spans the **largest distance**,
- It carries the **highest bending moments**,
- It is subject to the **strictest deflection limits**.

Transoms usually play a secondary structural role, as their spans are shorter and bending moments are lower.

2.16.3 Deflection Limits for Profiles (L/200 – L/250 – L/300)

Deflection limits for mullions and transoms are tightly linked to glass design; the two must be compatible.

Typical deflection limits are:

- **Serviceability Limit State (SLS)**:
    - L/200L/200L/200 or L/250L/250L/250 for mullions and transoms,
- For improved compatibility with glass and bitelines:
    - L/300L/300L/300 is often recommended,
- Maximum absolute deflection:
    - Commonly limited to **15–20 mm**.

These limits are required because excessive deflection can cause:

- Poor seating of the **pressure plate**, leading to bite loss,
- Loss of gasket contact and **water leakage**,
- Increased **edge stresses** in glass,
- Visibly **wavy panel surfaces** and aesthetic issues.

In high-rise buildings, designers often adopt **L/300 or more stringent limits** instead of L/250 to reduce motion and improve glass performance.

2.16.4 Selection of Profile Depth and Calculation of Moment of Inertia

A mullion's load-carrying capacity is strongly dependent on its **moment of inertia**.

Factors affecting the moment of inertia include:

- Profile depth hhh (the dominant parameter),
- Wall thickness,
- Symmetry and shape of the box section,
- Use of **reinforcement plates** or **steel inserts**.

A typical design approach is as follows:

1. Determine the **design wind pressure** qqq (kN/m²).
2. Define **panel height** hhh and **width** bbb.
3. Establish the mullion **span** LLL (storey height minus seating allowances).
4. Compute the maximum bending moment for a uniformly distributed load:

Mmax⁡=qL28M_{\max} = \frac{q L^2}{8}Mmax=8qL2

5. Determine the required moment of inertia IxI_xIx:

Ix≥Mmax⁡×103σallow·yI_x \ge \frac{M_{\max} \times 10^3}{\sigma_{allow} \cdot y}Ix≥σallow ·yMmax×103

where σallow\sigma_{allow}σallow is the allowable stress and yyy is the distance from the neutral axis to the extreme fibre.

6. Check deflection:

δ=5qL4384EIx\delta = \frac{5 q L^4}{384 E I_x}δ=384EIx5qL4

If the mullion proves insufficient:

- The **profile depth** can be increased,
- A stiffer **pressure plate** may be selected,
- A **steel reinforcement** can be added,
- Anchor spacing and locations may be **optimised**.

2.16.5 Special Requirements for Mullions in High-Rise Buildings

Above approximately **50–60 m**, wind loads increase significantly. In such cases:

- Mullion bending moments become much larger,
- Serviceability deflection limits are more difficult to satisfy,
- Glass thickness requirements increase,
- Anchor forces and rotations become more critical.

Common strategies to address these challenges include:

1. Use of **deep mullions** (e.g. 160–220 mm or more),
2. Adding a **steel box section** or plate to the back of the mullion,
3. Designing **split mullions** to facilitate transport and erection,
4. Reducing anchor spacing (shorter effective spans),
5. Employing **heavy box-to-box carrier systems** for primary support.

For these configurations, **3D structural analysis** using software such as SAP2000, Robot Structural Analysis or specialised façade software (e.g. LogiKal, SchüCal) is standard practice.

2.16.6 Influence of Anchors on Profiles and Structure

Anchors act as the **mechanical joints** between mullions and the primary structure.

Typical anchor behaviour:

- The **top anchor** is often designed as a **slotted (sliding)** connection to accommodate thermal expansion and contraction.

- The **bottom anchor** is typically a **fixed** support, taking the vertical dead load of the façade.

Inadequate anchor design can lead to:

- Unwanted **mullion bending** and secondary moments,
- Misalignment between glass and frame (**axis offsets**),
- Poor seating of the pressure plate and gasket,
- Excessive localised loads on the profile at the anchor location.

Anchor design must be checked under **wind loads** and, in seismic regions, under **inter-storey drift** demands. In this chapter, the focus is limited to static and dynamic wind effects; seismic effects are deliberately excluded from the scope.

2.16.7 Buckling, Lateral–Torsional Instability and Torsion of Profiles

Because aluminium profiles often have **thin wall thicknesses**, they are susceptible to:

- **Lateral buckling**,
- **Torsional deformation**,
- **Local crushing** or indentation.

This is particularly critical around **transom connections**, where:

- Excessive tightening of screws,
- Highly concentrated loads from pressure plates,
- Poor installation tolerances

can induce torsional rotations of the profile. These rotations may alter the **bearing surface** of the glass and compromise uniform load transfer.

2.16.8 Final Design Stage: SLS–ULS Checks for Profiles

The profile design process is considered complete only when both **serviceability** and **ultimate** limit states are satisfied.

Serviceability Limit State (SLS)

- Verification of **deflection** (L/200 – L/250 – L/300, as applicable),
- Long-term **fatigue resistance** of connection screws and brackets,
- Control of **gasket compression** within allowable limits,
- Compatibility with **glass bite** and IGU performance.

Ultimate Limit State (ULS)

- Maximum stresses in the profile under factored loads,

- Shear force **VVV** in anchors and brackets,
- Bending moment **MMM** transferred to the anchor and primary structure,
- Pull-out and failure resistance of **pressure plates** and fasteners.

Once both SLS and ULS requirements are met, the selected profile configuration can be regarded as **structurally and functionally adequate** for the specified wind loading regime.