ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Complex unitized curtain wall numerical analysis and full-scale test assessment of high-rise buildings for SLS: A case study on 4B+G+48 CBE_HQ building project

By: Hiruy Tekeste

A thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Degree of Master of Science in Structural Engineering.

Advisor: Dr-Ing. Girma Zerayohannes

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Approved by the Board of Examiners

Advisor	**Signature**	**Date**
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External Examiner	**Signature**	**Date**
Chairperson	**Signature**	**Date**

DECLARATION

I certify that this research work titled "**Complex unitized curtain wall numerical analysis and full-scale test assessment of high-rise buildings for SLS: A case study on 4B+G+48 CBE_HQ building project**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged/referred.

HIRUY TEKESTE

DATE: October 07, 2020

ABSTRACT

The building façade is the face of a building which gives the building its own unique identity. In modern High-rise building constructions, even with complex shapes, a unitized curtain wall system is the primary choice. However, this practice of using unitized curtain walls for complex façades brings a lot of design and construction challenges related to movement accommodation, weather control, and façade structural stability. The new CBE HQ building is one with a complex façade due to the existence of attached decorative elements and the doubly sheared /sloped/ panels. These panels require the spanning mullions and the stack joints of the specific panels to be assembled using special connectors. This thesis deals with the investigation and comparison of the numerical analysis and full-scale test results of the unitized curtain wall mullions for serviceability limit state. The deflection results of the numerical analysis and the test for the selected members including the joined mullions are presented, discussed, and compared. Although all the measured deflection data are within the allowable limit, for the continuous members the numerical analysis provides higher deflection values while for joined mullion members the full-scale test displacement values at the joint are found to be larger. This is found to be due to the gaps provided for construction tolerance at the support which also shows a negative impact on the structural stability of the support and leakage control of the curtain wall. Also, this paper shows the importance of full-scale testing for complex façades as a final deciding factor. A detailed introduction of curtain wall systems is also included in this thesis to provide the basic knowledge for the readers.

Keywords: FAÇADE, UNITIZED CURTAIN WALL, FULL-SCALE CURTAIN WALL TEST

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CBE_HQ – Commercial Bank of Ethiopia _ Head Quarter project

FE – Finite Element

IGU- Insulating Glass Unit

PMU- Performance Mock-up Unit

SLS – Serviceability Limit State

1 INTRODUCTION

1.1 Background and motivation

In Ethiopia, not only the unitized curtain wall system but the Curtainwall by itself is a new technology as a building façade. The usage of Aluminum framed glass curtain walls as an exterior wall has only three decades of history in the country and less than a century globally. It can be considered as an emerging technology compared with other forms of façade walls.

Although there are many types of curtain walls on the global market, the Stick-built curtain wall system was the only dominant curtain wall type in the country's building construction industry. Nowadays, some buildings started to use a unitized curtain wall system instead of a stick-built system as a building façade. The main factor for the current choice of unitized curtain wall over the stick-built system is the emergence of the financial center in the capital city, Addis Ababa, which embraces high-rise building construction which in turn requires high-quality façades.

The Unitized curtain wall system is one type of curtain wall in which the panels are assembled in the workshop with high-quality control and installed on-site as a panel instead of installing the components on-site item by item as in the case of a stick-built system. One of the basic advantages of a unitized curtain wall system is its ability to accommodate movements caused by temperature differences, vertical live load-related movements, and also movements related to inter-story drifts.

The current state of the art in high-rise building construction focuses on complex shape buildings with complex facades. Such complex facades are the major concerns when choosing the type of façade with high-performance capacity. Unitized curtain wall becomes the prime choice for such complex high-rise building facades due to its attainable high-quality construction and also its ability to accommodate movements. Any hindrance to this movement accommodation might affect the integrity of the curtain wall and it might lead to structural and/or performance failures.

In this thesis paper, the complex unitized curtain wall of the new CBE headquarters building façade having both inward and outward sloped unitized curtain wall panels aluminum mullion members (including the joined mullions) will be investigated with numerical analysis and full-scale tests for serviceability limit state.

On the other hand, the building construction stakeholders such as the regulating government bodies, owners, consultants, contractors, and even the local façade subcontractors lack the basic knowledge required to perform façade design, construction, and inspections. Although the cost of a Curtain wall in a single building project is covering as high as a quarter of the building construction cost, yet no standards are being implemented and even no formal Education have been given to all stakeholders in the country.

Despite this knowledge gap and lack of binding standards in the industry, the globally accepted new façade technologies are being practiced in the country nowadays. The current state of the art metal-framed glass curtain wall type which is being implemented globally, especially for high rise buildings, is the energy-efficient unitized curtain wall system. And yet, we are not in a position where we can choose or investigate the best and energy-efficient type of facades and glazing technologies that suits our environment and geographical location factors.

The motivation behind this thesis paper is the desire to equip professionals with basic tools for facade design, construction, and inspection and also to pave the way for standardizing the façade construction practice in the country with state-of-the-art technologies. The basic awareness creation is an equally important aspect of this thesis paper.

At the same time, the other motivation for this paper is the need to check and compare the numerical analysis and test results of complex unitized curtain walls with special emphasis for the joined mullion members.

1.2 Significance of the study

This thesis paper has two main significance. The first one is it will create the basic know-how about building façade types, different types of curtain wall systems, components, and materials for the stakeholders of the building construction. At the same time the curtain wall performance requirements, design concepts, and full-scale tests are addressed just to pave the way for future local practices, studies, and researches.

The second significance of the study is it will try to contribute to the developing science of building façade by analyzing the scenario of complex unitized curtain wall mullion members for SLS. It tries to do the comparison between the numerical analysis and the test outputs.

1.3 Objective of the study

1.3.1 General Objective

The general objective of this thesis paper is to create awareness about building façades and lay the foundation for future studies. The thesis paper doesn't only focus on the subject matter but also presents the basic knowledge about the curtain wall.

As a pioneer thesis paper dedicated to addressing the subject of the curtain wall in Ethiopia, its general objective is based on providing basic information about the curtain wall. It also aims to put the foundation for future studies and researches on curtain walls suited to our country based on our geographical location, seismic zones, and environment. This in turn will influence the practices of designing and constructing a curtain wall to be knowledge-driven instead of just following the current unscientific approach.

The other general objective of this thesis paper is to show the general concept, design, and construction of curtain walls by giving special emphasis to the Unitized curtain wall as this technology is new to our country. As most of the current building projects that use unitized curtain wall as exterior walls are being constructed by foreign International companies, this paper also aims to equip local professional Architects and Engineers with the basic knowledge about the unitized system to better understand and manage their projects.

1.3.2 Specific Objective

The specific objectives of this paper are:

1. To check and discuss the numerical analysis and test outputs of the doubly sheared complex unitized curtain wall system of the new CBE headquarter building against the deflection requirement.
2. Checking the effect of using a joined Aluminium mullion member on unitized curtain wall for serviceability limit state (deflection criteria specifically).
3. To see whether the numerical structural analysis model predicts the member deflection values of the complex unitized curtain wall by comparing with the full-scale test results.

1.4 Scope

The scope of this thesis paper focuses on checking the unitized curtain wall of the new headquarter high-rise building project of Commercial Bank of Ethiopia (CBE) based on the numerical analysis and full-scale test. Although the subject matter by itself is broad and needs detailed and controlled research, this paper tries to seize the actual performed test of the project's unitized curtain wall as an opportunity, with all its limitations, just to see the effects of using joined mullion members on unitized curtain wall panels for the structural performance requirements. The sharp-cornered of the joined stack joint (male + female transom) members is not investigated in this thesis paper.

The Finite Element analysis is limited to the general frame finite element analysis and not to specifically modeling the actual scenario of the unitized curtain walls panel to panel connection. This might have its shortcomings on the results gained from the analysis and the full-scale test.

On the other hand, for the full-scale test, the test is done for checking the CBE building project curtain wall test to evaluate the actual performance of the system. For the sake of this thesis paper, only some additional sensors are added to the actual test setup.

1.5 Methodology

As stated above on the general scope of this thesis paper, creating the basic knowledge among the building construction stakeholders is one of the interest areas of this thesis paper. To address this aspect of the thesis scope one chapter is dedicated just to discuss in detail the basics of building façade with special emphasis on curtain wall types, components, materials, and performance requirements. Briefly discussing the basics of the curtain wall is also mandatory for any interested readers of this thesis paper with no or limited knowledge about the curtain wall.

To address the subject matter of this paper both Finite Element software-based structural analysis and also full-scale tests have been conducted. Although the test is performed actually for the building project, some additional sensors were placed on locations of interest to get measurement data to compare with the software output.

The basic methodology used for this paper is first a detailed description about curtain wall is discussed and the subject matter related literature review presented. Then, the Finite element analysis model and design process are shown for the selected specimen of the case study project Commercial Bank of Ethiopia's new headquarters project unitized curtain wall.

The detailed test steps, test procedures, and the corresponding results are also presented. Finally, a discussion and comparison between the numerical analysis output and the test results is done and recommendations are forwarded.

1.6 Organization

Chapter one is the introduction part including the background and motivation, significance of the study, objectives of the thesis (both general and specific objectives), Scope, methodology, and chapter organization sections.

Chapter two is regarding the basics of building façade. The chapter tries to cover types of metal-glass façade, components of curtain walls, curtain wall materials, and the performance requirements and tests of curtain wall sections.

Chapter three is the literature review with a general introduction, high-rise building façades, stick-built vs unitized curtain wall systems, complex Unitized curtain wall systems, design principles of unitized curtain walls, and full-height tests of curtain wall sections.

Chapter four is about the numerical analysis of the CBE unitized curtain wall with a general overview of the CBE project, Design loads, Finite Element Modeling, and FE Analysis sections.

Chapter five is the full-scale test of the unitized curtain wall with introduction, test specimen assembly, test setup, and performance test sections.

Chapter six is about the results discussion and comparison with general Introduction, finite element analysis result, full-height specimen test result, and results comparison and discussion sections.

Chapter seven is for the conclusion and recommendations of the study.

2 BASICS OF BUILDING FAÇADE

The word Façade, meaning “face” or “frontage” in French, is used to express the skin of a building, usually, the front side, where architects put the unique appearance of the building. Building façade’s main purpose is to provide the interface between the environment outside and the user inside.

Among the façade systems available on the market, the Metal-Glass façade system gained global acceptance due to its superior elegance, lightweight characteristics, maximized transparency, and adaptability to the required shape. Metal-Glass façade system is a type of building façade that uses metal as a frame (support) and glass as an infill.

2.1 Types of Metal-Glass Facades

The metal-glass façade (commonly referred to as *Aluminum framed curtain wall*) is an emerging building façade technology that gained superior global acceptance. The reasons include the unparalleled opportunity provided by it to obtain the maximum amount of daylight and view, the cost savings compared with other exterior wall cladding systems, and the recent technological advancements in the thermal and structural performance of the glass wall systems (Mehta et al., 2013).

There are numerous types of metal-glass façades in the market. Due to the rapid technological advancement in the industry, finding to date and brief classification of metal-glass façade systems is difficult. Many literatures have classified metal-glass facades into many categories but for this thesis paper, they are grouped into three major groups based on the type of glass support system used and their form. These are:

1. Metal-framed glass façade system
2. Point-fixed structural glass façade system
3. Grid shell façade system

2.1.1 Metal-framed glass façade system

A metal-framed glass façade is a type of building façade that uses ***metal*** as a frame (support) and ***glass*** as an infill. The glass is supported by a continuous metal frame in two, three, or four sides of its edge. The most common metal used as a load-bearing frame structure to support the glass in building façade construction is the *Aluminum alloy profile*.

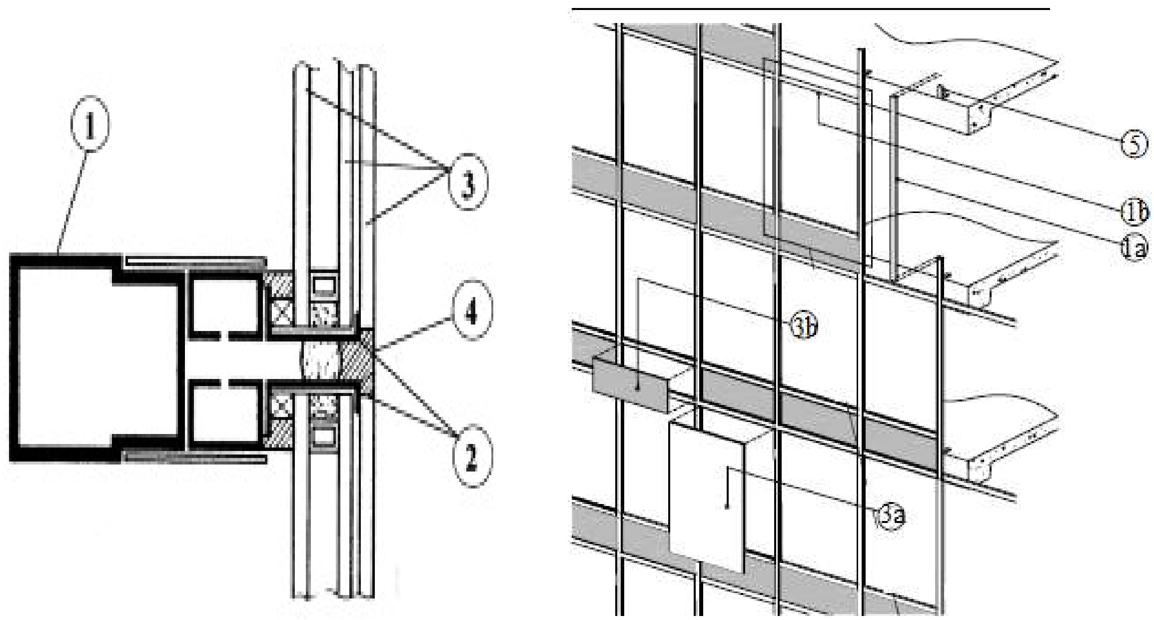


Figure 2-1 Metal framed glass façade system: (1) Load Bearing Structure, (1a) Mullion, (1b) Rail, (2) profile system, (3) Glazing, (3a) Vision panel, (3b) Spandrel panel, (4) Fastening system and (5) Anchor (Kallioniemi, 1999)

Aluminum framed glass façade systems are classified into two major groups based on the *construction method* used:

1. Window wall (panel façade) and
2. curtain wall

2.1.1.1 Window wall (panel façade)

The American Architectural Manufacturers Association (AAMA), defines window wall as follows *"A type of metal curtain wall installed between floors or between floor and roof and typically composed of vertical and horizontal framing members, containing operable sash or ventilators, fixed lights or opaque panels or any combination thereof"*

Window wall is often used for residential buildings as it allows easy customization like adding windows and doors. The wall can also be recessed to add balconies outside the wall. The nature of the window wall, breaking up at each floor by the building slab gives the following advantage over the curtain wall:

- ✓ require less engineering [design]
- ✓ Safe installation and easy to repair
- ✓ More cost-effective and efficient
- ✓ Good fire control from floor to floor
- ✓ Less noise transfers
- ✓ Less energy loss

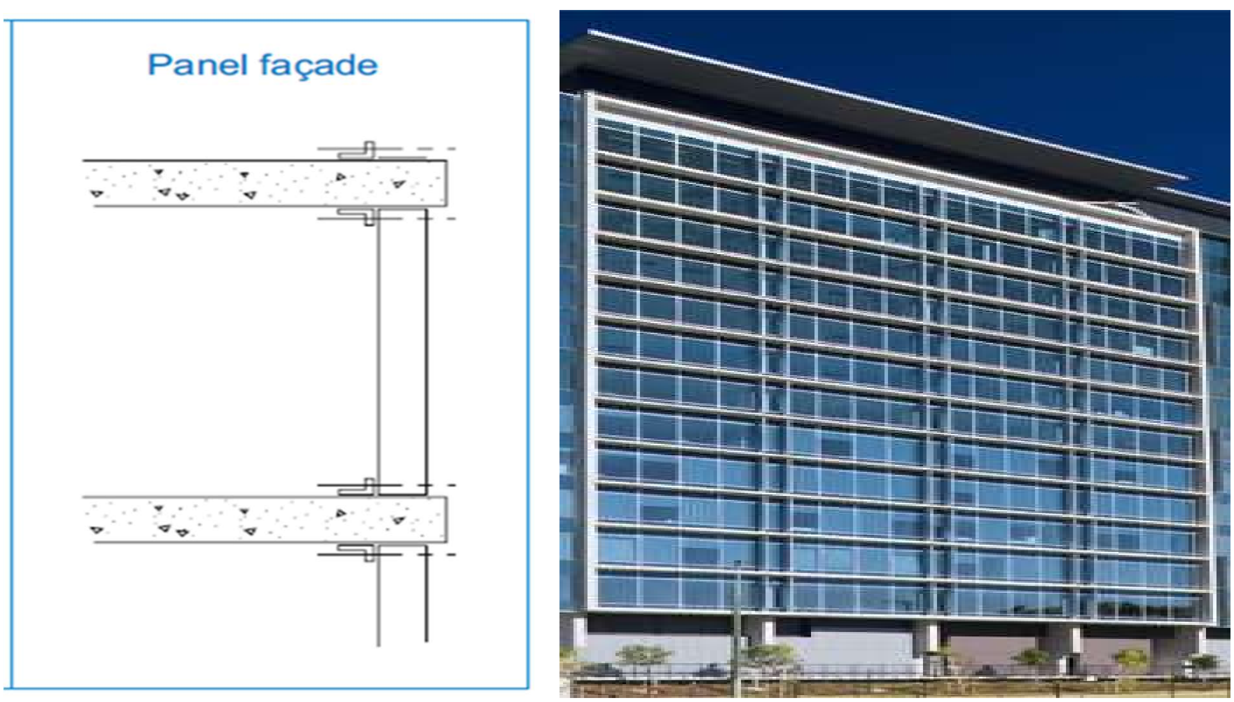


Figure 2-2: Window walls

2.1.1.2 Curtain wall

AAMA defines a curtain wall as:

"An exterior curtain wall which may consist entirely or principally of metal, or maybe a combination of metal, glass and other surfacing materials supported by or within a metal framework"

The curtain wall is the most commonly used façade system for buildings. Its expanded transparency, lightweight, aesthetical value, and adaptability to the required forms make the curtain wall favorable by the Architects and designers on the market.

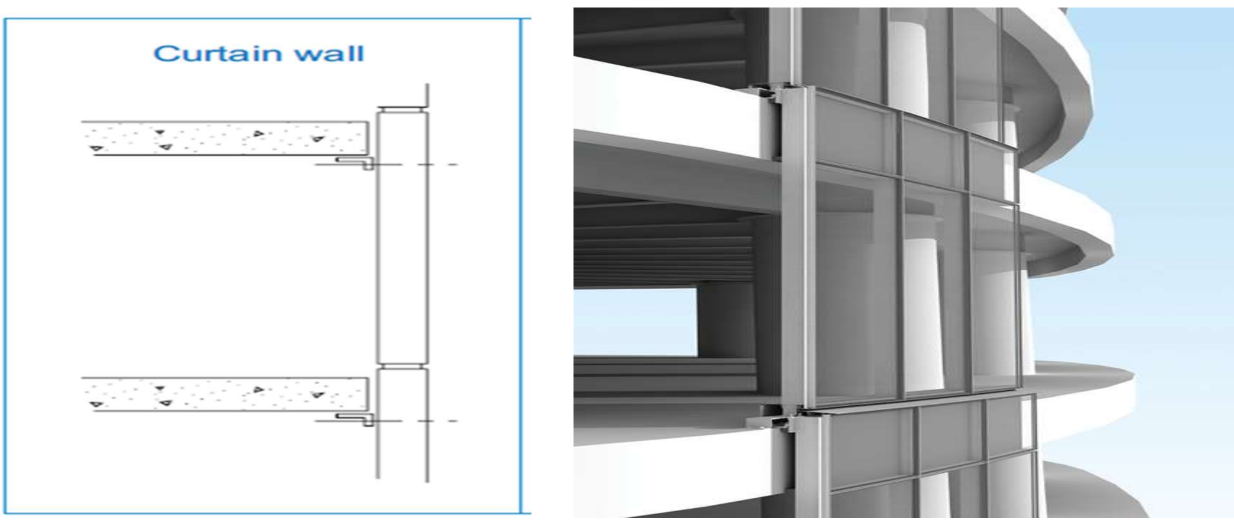


Figure 2-3: Curtain walls

Maintaining the basic concept of covering the building exterior as a curtain, curtain walls can be classified based on Architectural, construction methodology, and familiarity with the market as shown below.

2.1.1.3 Classification of curtain walls

There are many types of Aluminum framed curtain wall classification criteria. Among these criteria's classification based on *wall type*, *classification based on the method of assembly (erection), classification based on Architectural (glazing) types,* and *classification based on the method of glazing installation* are the most common ones.

2.1.1.3.1 Classification based on wall type (Aluminum profile availability)

Curtain walls are classified into two generic groups based on the ***market availability*** of the extruded Aluminum profiles. These are:

A. Standard curtain wall system and
B. Custom made curtain wall system

i. Standard curtain wall system

The curtain wall type and the Aluminum profiles used in standard curtain wall systems are standardized and manufactured by the manufacturer without having any prior production request. The profiles can be purchased from suppliers as the manufacturer catalog is available.

ii. Custom made curtain wall system

In custom-made curtain wall systems, aluminum profiles are not readily available on the market. Specific Aluminum design and detailing is required for single or multiple projects. The Aluminum extruders are expected to prepare specific dies before the aluminum extrusion. The Canadian practice guide for glass and metal curtain walls (CMHC, 2004) provides a comparison between *standard* and *custom-made* curtain wall types as presented in Table 2-1.

Table 2-1: Comparison of standard and custom-made curtain walls

WALL TYPE	CHARACTERISTICS AND FEATURES
A. STANDARD	• Details and components designed and standardized by manufacturer • Manufacturers sell through a dealer network • Manufacturers stock in standard lengths typically 6.5 to 8.2 m • Standard finishes although custom finishes available • Typical frame width 50 mm (2 inches) or 63.5 mm (2 1⁄2 inches), frame depth 75 to 150 mm (3 to 6 inches) • Manufacturers catalog information readily available • "Standard" designation applies only to components not to the potential arrangement of components
B. **CUSTOM**	• Details and components designed specifically for a single project or group of projects • Materials generally not available on the open market but restricted to a single supplier or installer • Minimum size of the project required to justify custom extrusions • Allows optimum use of material and flexibility to meet architectural requirements • Component dimensions and cross-sections often architecturally distinct

2.1.1.3.2 Classification based on the method of assembly (erection)

The American Architectural Manufacturers Association (AAMA) classifies curtain wall systems into five types based on their ***anatomy***. The first two systems (stick-built and unitized systems) are the most widely used nowadays and the other three are somehow neither common nor promoted for new buildings nowadays.

1) Stick-built (frame) systems
2) Unitized (Unit panel) systems
3) Unit and mullion (semi-unitized) systems
4) Panel systems
5) Column cover and spandrel systems

1. Stick-built systems

The stick-built system, as the name implies, is a method of curtain wall construction in which all the components are installed on-site piece-by-piece. This curtain wall system is the first type developed by manufacturers and remains the most common one around the world and in Ethiopia. Almost all materials used for this system are off-the-shelf (standard) materials which in turn favors low cost and short lead time of construction for small projects.

Figure 2-4:Stick-built curtain wall

The stick-built system has the following merits and demerits (Wong, 2003).

Merits:

- ✓ Low cost, components can be made in standard design and stocked
- ✓ Less lead time required for design and fabrication
- ✓ Require relatively simple sections to form the mullions and transom
- ✓ Installation need simple tools

Demerits:

- ✓ More labour-intensive during installation
- ✓ Higher risk of leakage due to in-situ joints between mullion and panels
- ✓ troublesome and inconsistent on-site members fixing
- ✓ Require more installation time

2. Unitized (Unit panel) System

A curtain wall system with each panel assembled in a workshop under tight supervision and installed on-site panel by panel is referred to as a unitized curtain wall system. A unitized curtain wall will have the same components as a stick-built curtain wall system. However, instead of assembling the glass and aluminum curtain wall in the field, most of the system components are assembled in a plant under controlled working conditions. This promotes quality assembly and allows for fabrication lead-time and rapid closure of the building.

Unlike the stick-built system, the edge mullions and transoms are extruded as two sections comprising male and female profile sections to make a single profile instead of extruding a single tubular section. In this system the panels are installed in an orderly fashion, usually starting from the bottom of the building and going around each floor and up the building. The following are the merits and demerits of the Unitized curtain wall system (Wong, 2003).

Figure 2-5: Unitized (unit panel) curtain wall system

Merits:

- ✓ Easy to install merely by securing the modulated panels onto the building exterior
- ✓ Saving up a lot of manpower due to ease of installation.

- ✓ Higher performance units can be produced to meet stringent requirements due to better control under the factory environment.
- ✓ Preferable for buildings with large walling areas

<u>Demerits:</u>

- ✓ It requires a longer lead time to carry out the coordination, design, and fabrication of the system/units.
- ✓ Require higher dimensional accuracy of the building structure for ease of installation
- ✓ Heavy lifting machines might be required to lift panels
- ✓ Difficult to carry out replacement or maintenance

3. Unit and mullion (semi-unitized) system

The unit and mullion system combines the advantages of both the stick system as well as the unitized system. It is constructed by first installing the mullions; subsequently, factory-assembled units are placed between the mullions.

Because the system is a compromise between the stick and unitized systems, it has the advantages and disadvantages of both, i.e., its transportation cost is lower than that of the unitized system but greater than that of the stick system. A greater degree of site adjustability is available in the unit and mullion system, but it is less than that of the stick system.

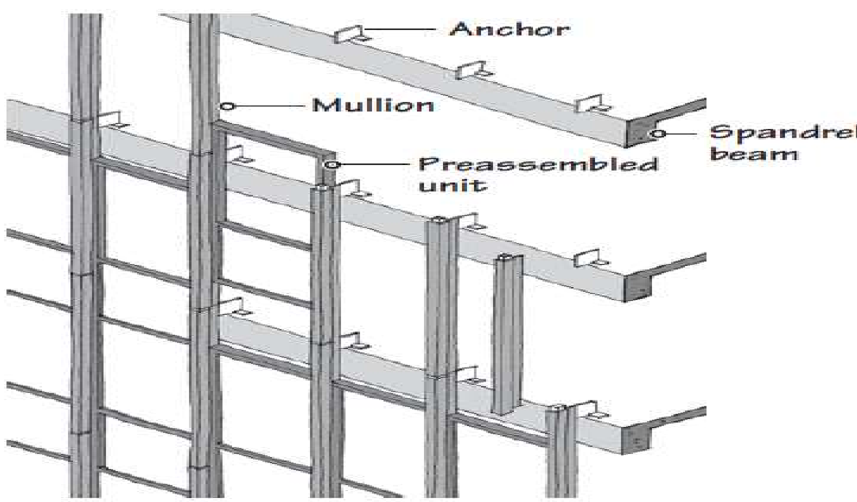


Figure 2-6:Semi-unitized curtain wall system

4. **Panel system**

The panel system consists of preassembled (and sometimes pre-glazed) homogeneous sheet metal panels with glass infill's that generally span from floor to floor. The curtain wall's appearance is more integrated and comprehensive rather than a grid pattern of horizontal and vertical elements.

The panels can be formed by stamping or casting. The casting system is economical only where a large number of identical panels are needed.

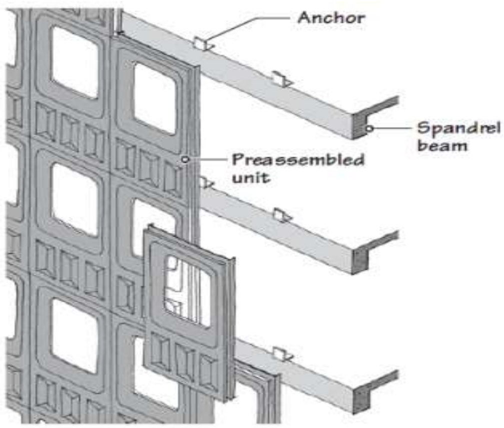


Figure 2-7: Panel system curtain wall

5. **Column cover and spandrel systems**

This system, though not a true glass curtain wall system, consists of separate column covers connected to spandrel covers that generally span from column to column. Infill glazing units may either be preassembled or assembled at the site like those of a stick-built system. The system provides an independent expression of the structural system rather than concealing it behind a (more homogeneous) wall.

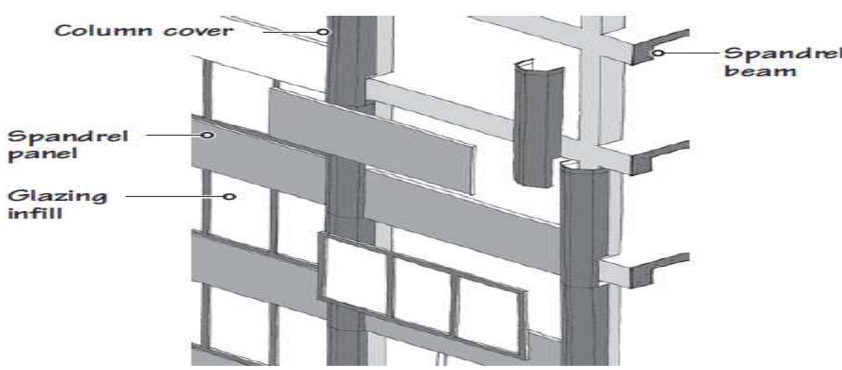


Figure 2-8: Column cover and spandrel system curtain wall

2.1.1.3.3 Classification based on Architectural (glazing) types

Curtain walls can also be classified based on their architectural output because of the specific details on how infill panels are supported (attached) with the framing grid and frame visibility from outside. There are three major types of glazing methods on the market. These are

1) Visible grid (exterior batten) system
2) Half visible grid system and
3) Structural silicone glazing system

1. Visible grid (exterior batten) system

The visible grid curtain wall system is the most commonly used form of glazing method which relies on pressure plates to hold infill panels against framing members. The frames are visible from outside both vertically and horizontally.

Figure 2-9:Visible grid curtain wall type

2. Half visible grid system

In this system, the two edges of the infill panel are adhered to framing members with structural silicone sealant and two edges are mechanically fixed using pressure plates. The frames are visible from outside either vertically or horizontally.

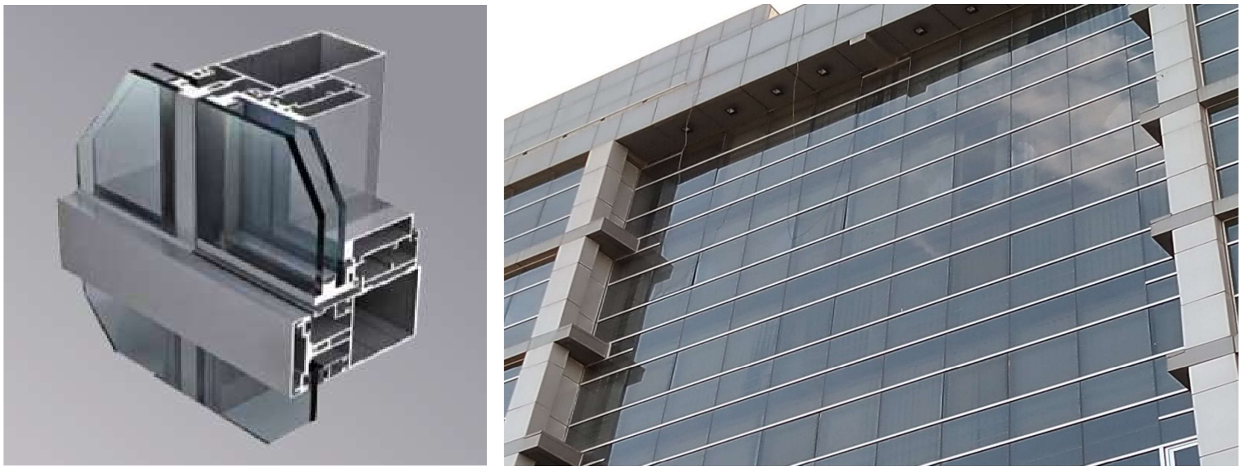


Figure 2-10: Half-visible grid curtain wall type

3. **Structural silicone sealant glazing system**

In this case, the supporting frame members of the curtain wall are completely concealed behind the glass, as the panes are not mechanically fixed to the profiles, but are adhered to them using a special type of adhesive called ***structural silicone***. This gives the façade a less solid appearance, due to the predominance of the reflection from the glass.

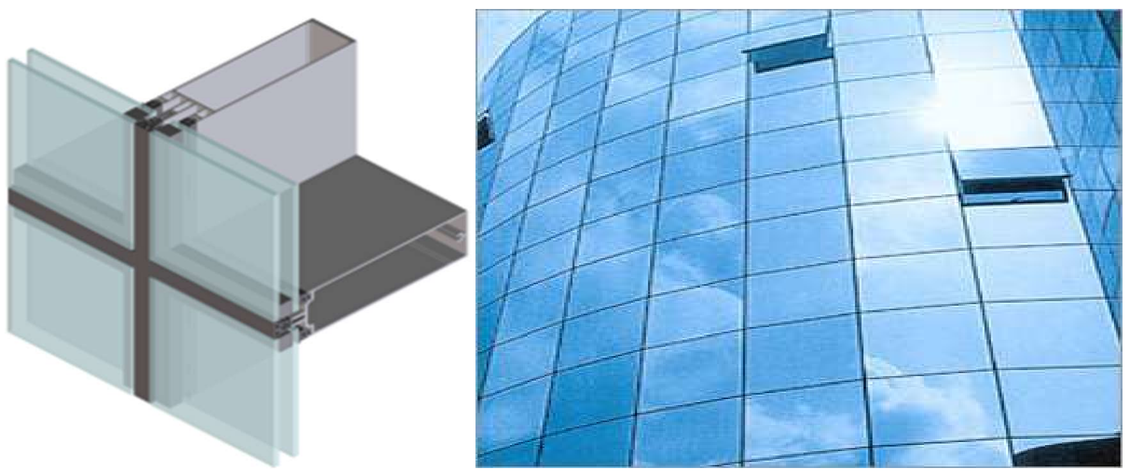


Figure 2-11: Structural silicone curtain wall type

2.1.2 Point-fixed structural glass façade system

The point-fixed structural glass façade system is one of the metal-glass façade systems on the market where the glasses are supported on a point at its corner instead of supporting it continues along its edge perimeter. This type of facade is a relatively recent class of building technology used where heightened transparency and a dematerialization of the structure are often predominant design objectives.

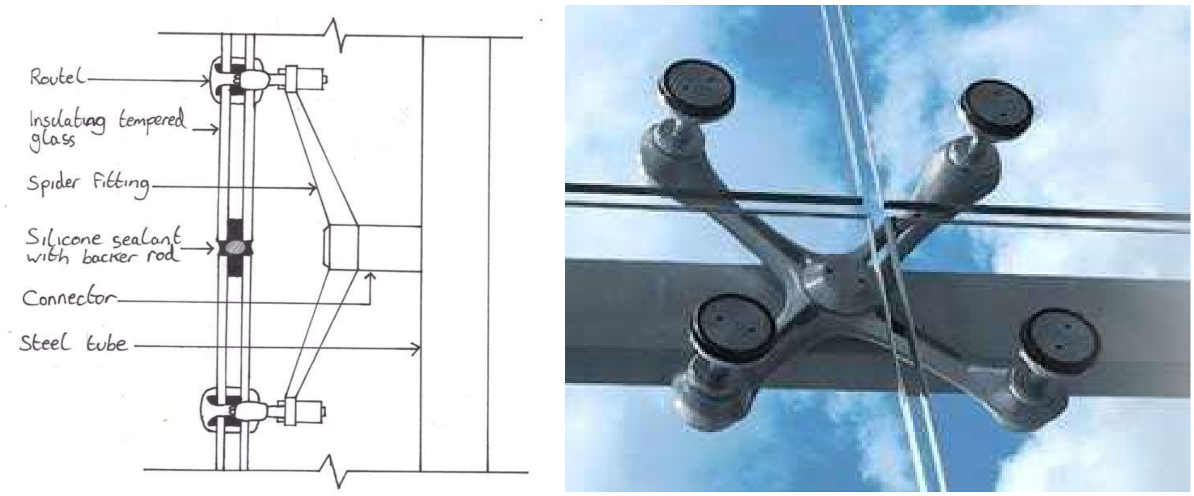


Figure 2-12: Point-fixed structural glass façade system

There are two basic forms of point-fixed glazing system used in SGFs: *point-fixed bolted fittings*, which transfer load by bearing, and *point-fixed clamped fittings (patched)*, that transfer load by friction, as shown in Figure below. Both fittings are used to hold the glass and transfer the glass self-weight as well as lateral loads to the structural support system.

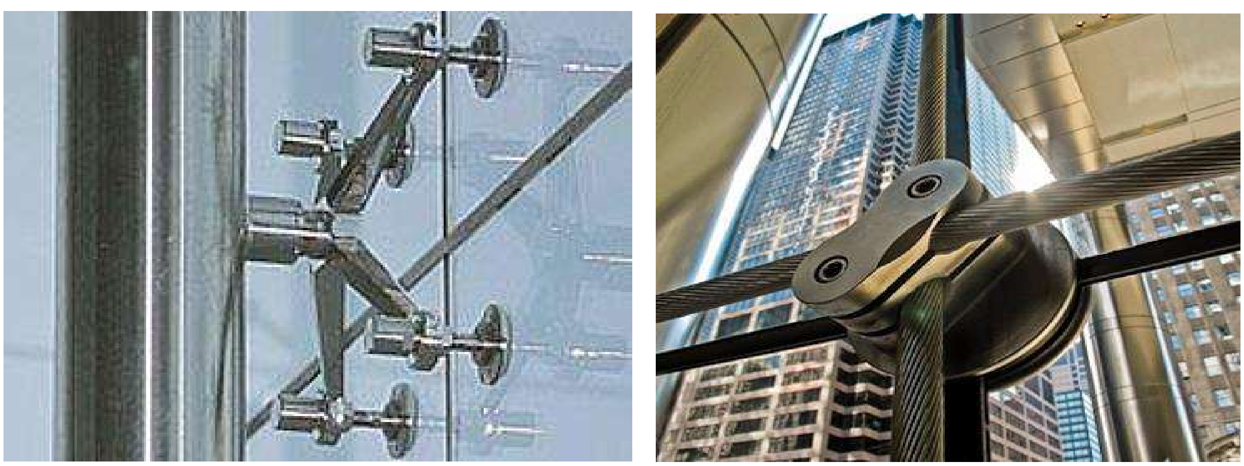


Figure 2-13: Point-Fixed Bolted comprises of glazing bolt and spider fittings (left), Point-Fixed Clamps are connected to cable structures (right)

2.1.3 Grid shell façade system

In the 21st century, as the free-form design grows in popularity, grid shells are becoming a universal structural solution, enabling the conflation of structure and skin (façade) into one single element (D. Turgut ÇIKI, 2007).

The name of the grid shell commonly describes a structure with the shape and strength of a double curvature shell but made of a grid instead of a solid surface. These structures can cross large spans with very few materials (Douthe et al., 2006). In this system, the glass can be supported by either a metal-framed system or a point-fixed system. Grid shell facades have a superior elegance while having no or limited vertical supports in between.

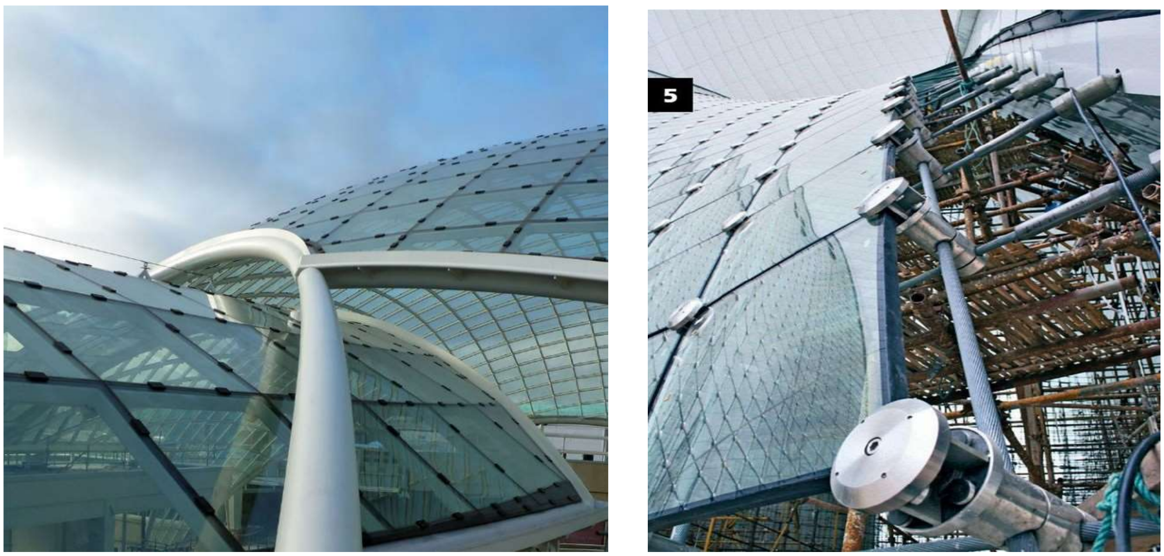


Figure 2-14: Grid shell façade system

2.2 Components of Curtainwall

Curtain wall construction comprises different materials (like glass and Aluminum composite panel (ACP) infills, Aluminum frames, stainless steel bolts, silicone sealants, etc.…) assembled to form a single wall. Both stick-built and unitized curtain wall systems have the below listed major components.

2.2.1 Glazing panel

A glazing panel is an infill material used to fill the gap in-between the Aluminum frames. The infill panels could be either a Vision panel (transparent) or a spandrel panel (opaque). Aluminum framed Curtain walls can be fully constructed from vision panels or in combination with spandrel panels.

2.2.1.1 Vision panel

The vision panel is the transparent part of a curtain wall that uses glass as an infill panel. This panel allows the natural daylight and air to enter the building as all vision glass and window openings are located in this part.

2.2.1.2 Spandrel panel

Spandrel panels are introduced on a curtain wall to conceal the buildings' structural elements from outside visibility. These panels are also suitable for the curtain wall's fire control system application. The infills can be either an opaque (fritted) glass or Aluminum plate materials that are capable of blocking direct visual contact.

Figure 2-15: Vision and spandrel panel

2.2.2 Glazing system

The glazing systems are components of the curtain wall that holds the glass in place and transfers the loads from the glazing to the load-bearing structures. Both stick-built and unitized curtain walls use mainly two types of glazing systems to support the glazing as follows:

- Pressure plate glazing system
- Structural silicone sealant glazing system

2.2.2.1 Pressure plate glazing system

Aluminum pressure plates are used to fasten the glazing panel to the load-bearing aluminum mullion and transom frame when the frame is required to be visible from the outside. The pressure plate is fixed to the Aluminum frame by using a screw and rubber gaskets are used to avoid direct contact between them and also as a water and air barrier.

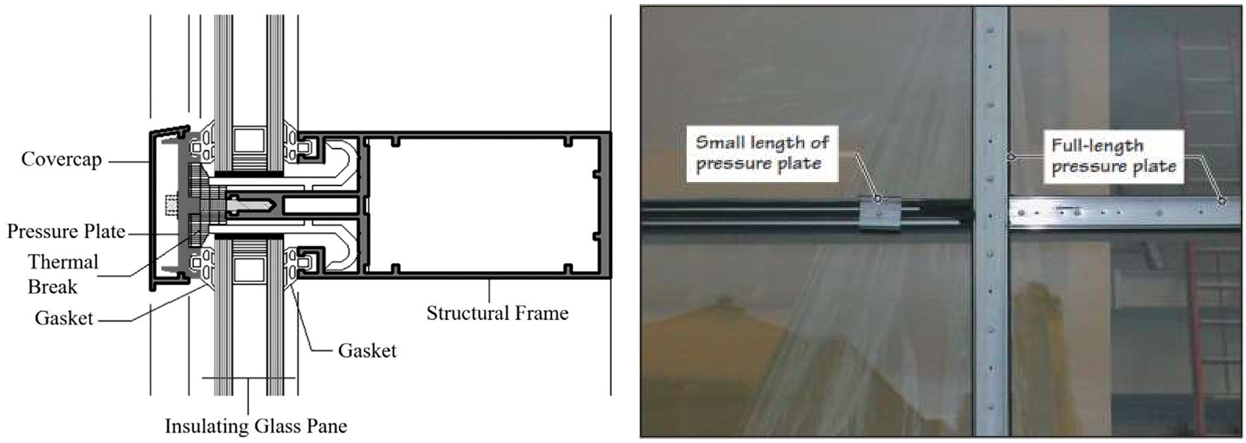


Figure 2-16: Pressure plate glazing system (Ýlhan & Aygün, 2006)and (Mehta et al., 2013))

2.2.2.2 Structural silicone sealant glazing

When the aluminum frame is not required to be visible from the outside, a structural silicone sealant glazing system will be used. The glazing panel is attached to the supporting Aluminum mullion and transom frame using a structural silicone sealant. The structural silicone sealant is a high strength sealant that is capable of carrying the glass and transfer the structural loads to the framing members.

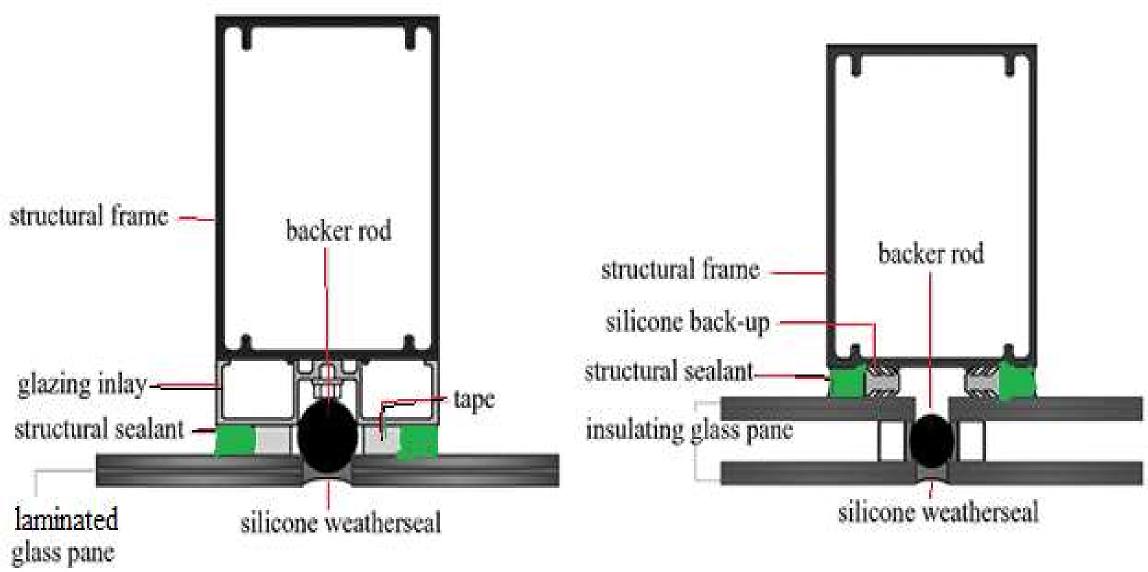


Figure 2-17: Structural silicone sealant glazing system (Ýlhan & Aygün, 2006)

2.2.3 Load bearing structure

Load-bearing structures in curtain walls are the Aluminum profile frames that withstand self-weight, wind, and other laterally imposed loads on the curtain wall and transfer them to the anchors attached to the building structure, or foundations. On both stick-built and unitized curtain walls, the Aluminum mullion (vertical member) and transom (horizontal member) are the load-bearing structures.

Aluminum mullion and transom profiles used for stick-built and unitized curtain wall systems are different in their form. For the stick-built system, the mullion and transom profiles are a single, rectangular (standard shape) extruded aluminum profiles. Whereas for the unitized system the mullions and edge transoms comprised of two (male and female) extruded aluminum profiles to make unit panels to fit at this point.

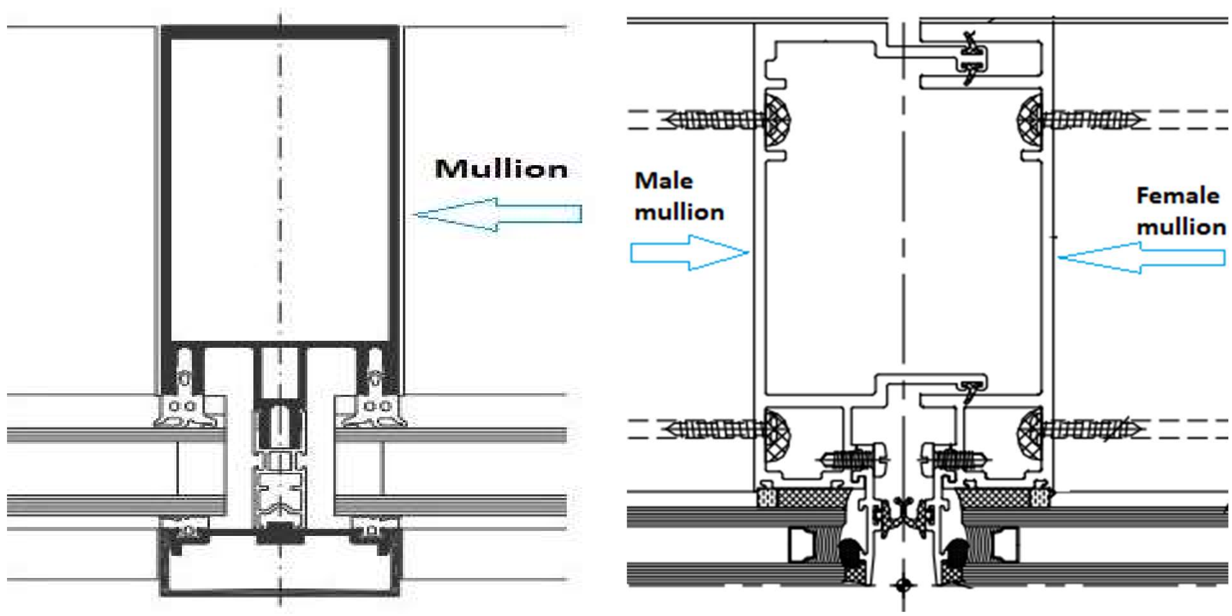


Figure 2-18: Stick-built system mullion (on the left) and unitized system mullion (on the right)

The standard Aluminum profile sections on the market are manufactured to withstand specific load intensities. When these sections are required to be used for higher load intensities larger than their designed load carrying capacity, some reinforcement methods can be implemented. The most widely used method is to enclose structural steel (or aluminum) sections within the mullions or transoms, as shown in the Figure below.

The enclosed steel sections and the mullions are fastened together to produce a composite action between them. Structural C- or I-sections are commonly used as enclosed sections. Channels provide the advantage of nesting, so that two or three channels may be used within the same mullion. The enclosed steel sections are suitably coated to prevent galvanic action between the aluminum and steel (Mehta et al., 2013).

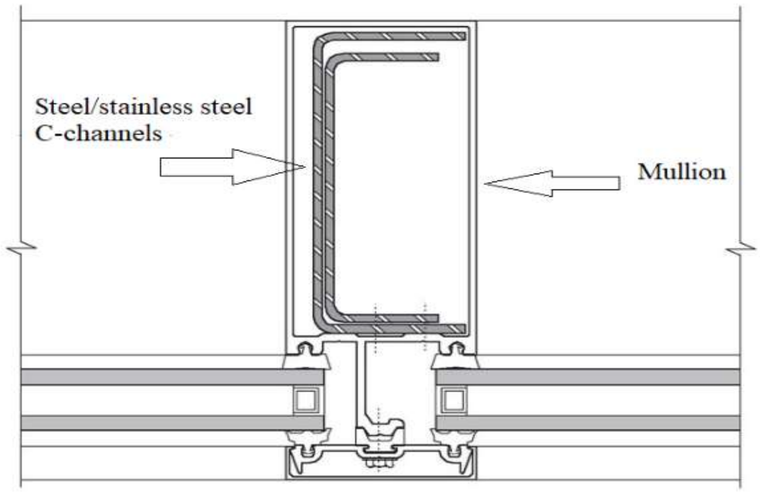


Figure 2-19: Steel-reinforced aluminum mullion

2.2.4 Connectors

Connectors in curtain wall construction are used to join the load-bearing structures to one another and also to the anchors. Manufacturers use various methods of connections and most of the curtain wall connection types are bolt connections instead of welding to entertain movement tolerances. Transom to mullion, mullion to mullion, and mullion to anchorage are the major connection points for both stick-built and unitized curtain wall assembly and installation.

2.2.4.1 Transom to mullion connection

A stick-built curtainwall system uses a shear block, a cut to size Aluminum extruded profile, for each transom to mullion connections. The shear block is first fastened to the mullion then the transoms are snapped over the shear block and secured using screws.

Whereas, unitized curtain wall transom to mullion connection is quite simple as it doesn't require any kind of shear blocks. The connection can be realized by simply drilling through either male or female mullions and fastening to the transom through the already available screw chase inside the transom using screws as shown below.

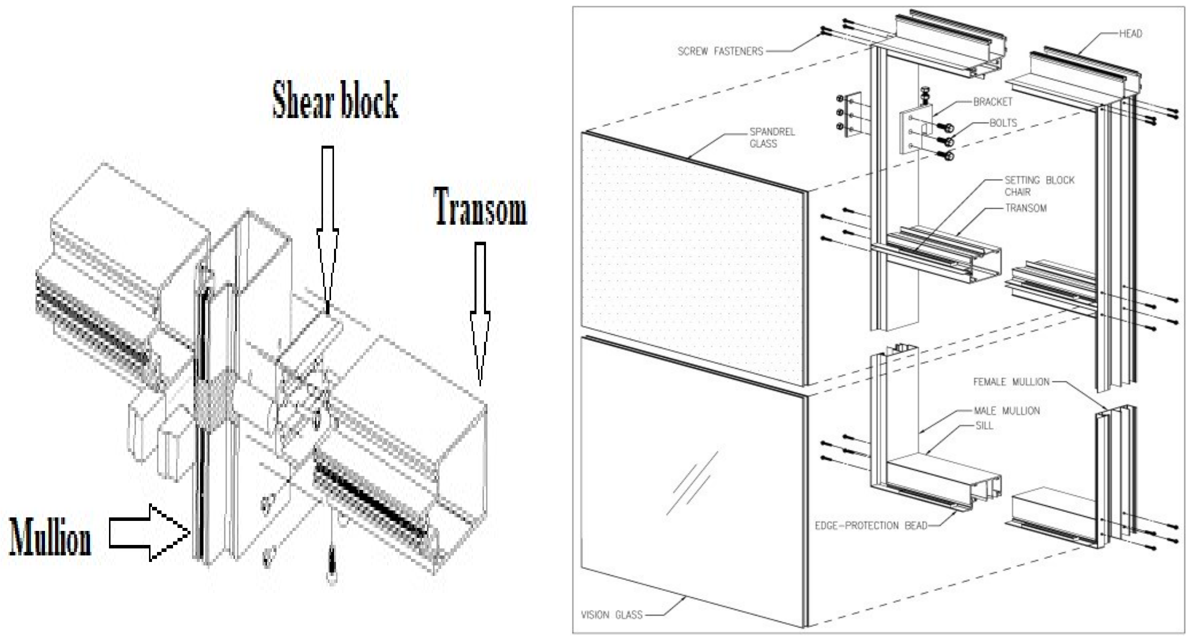


Figure 2-20: Transom to mullion connection on stick-built (left) and unitized system (right)

2.2.4.2 Mullion to mullion connections

To extend the mullions to the next floor a steel or aluminum splice (sleeve) is inserted and fastened to the bottom mullion then the top mullion snapped over the splice leaving some vertical gap as a thermal expansion joint. The gap of this joint must be determined based on the thermal movement of the mullion length, deflection of the supporting beam, and the creep in columns (if any).

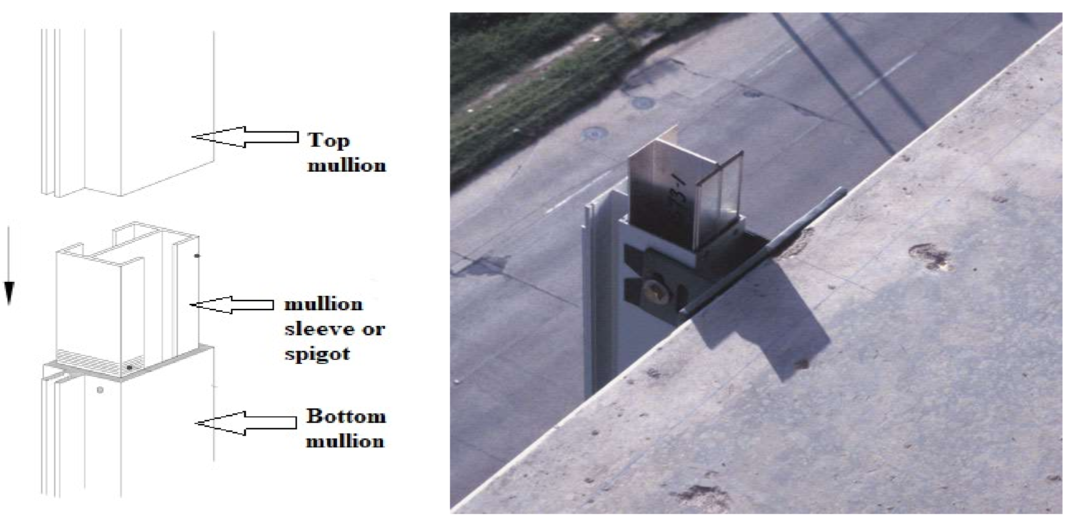


Figure 2-21: Mullion to mullion splicing used in stick-built system (CMHC, 2004; Mehta et al., 2013)

2.2.4.3 Panel to panel connections

For unitized curtain wall system construction, panel to panel aligners for both adjacent panels and top and bottom panels shall be used. A horizontal alignment clip is used to maintain the horizontal alignment between the two adjoining panels. This horizontal alignment clip is also used for the water penetration control, as a gutter, at the gap between two adjacent panels. Panel lifting lug (vertical alignment clip) is used to maintain the vertical alignment of the two panels in addition to its use as a lifting lug for unit panel installation.

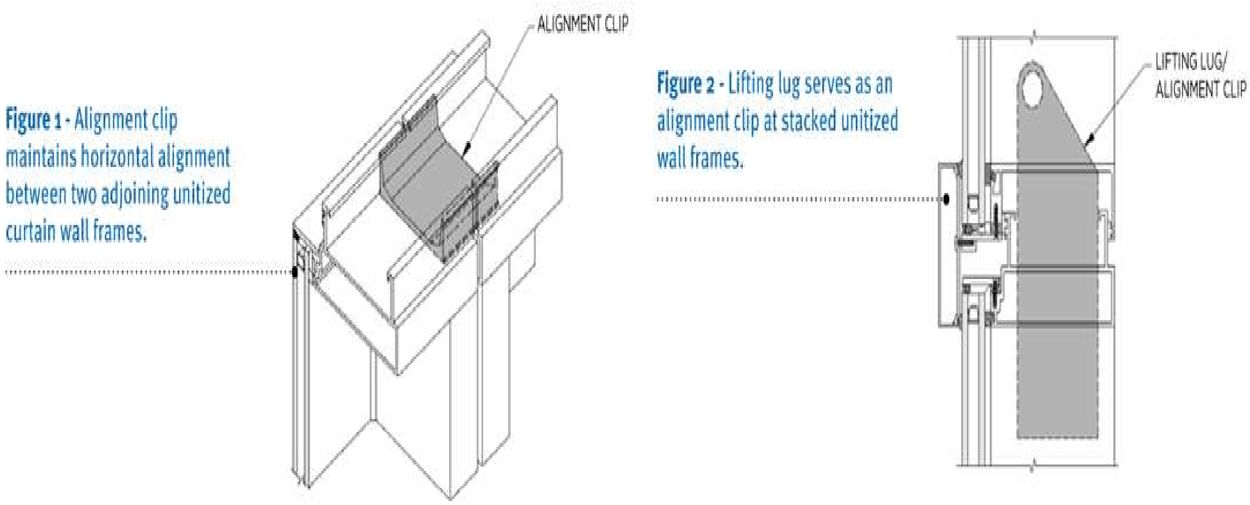
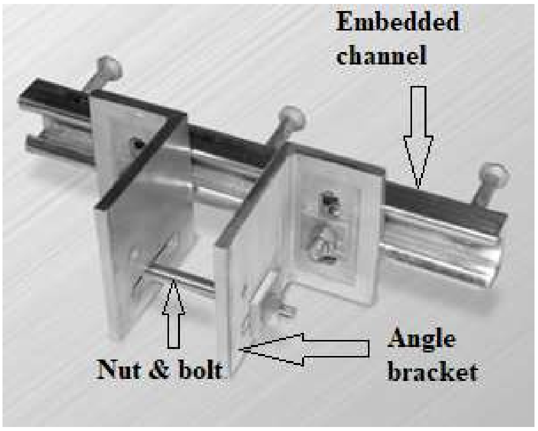


Figure 2-22: Horizontal and vertical alignment maintaining mechanism for unitized curtain wall

2.2.4.4 Mullion to anchor connectors

High-grade Aluminum profiles like (6061-T6) and steel sections are used as a bracket to connect the mullion to the embedded anchors or directly to the building structure. The brackets are bolted to the mullion and then to the proposed anchor system providing a slot to entertain different curtain wall movements. Different types of brackets are used for stick-built systems and unitized system curtain walls as shown below.



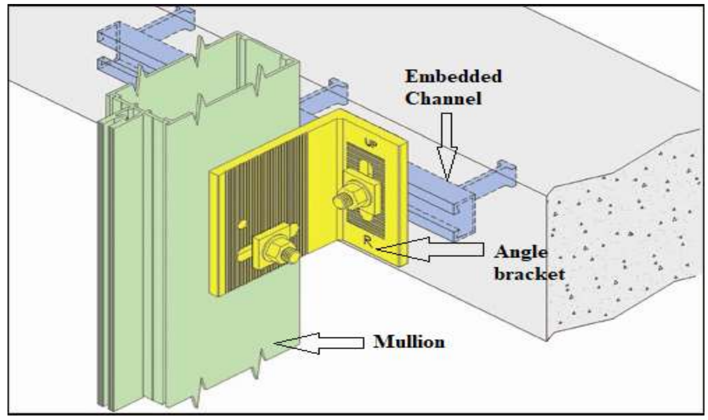


Figure 2-23: Brackets for stick-built curtain wall system

For the unitized curtain wall system, the vertical brackets shown below are the common bracket type used as a dead load anchor (DL anchor). Either slab top-mounted P-clip anchor system or side-mounted brackets are attached to the embedded channel or plate to give support for the vertical brackets providing a certain degree of movement tolerance for construction errors.

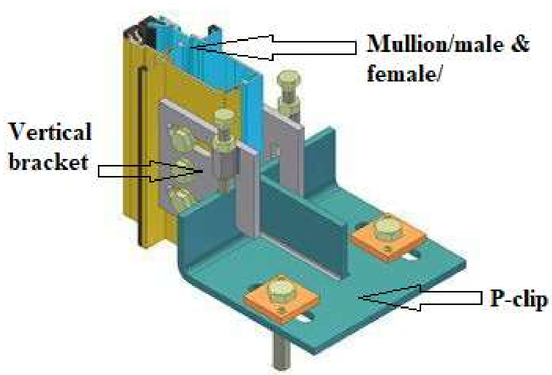


Figure 2-24: Brackets for a unitized curtain wall system

2.2.5 Anchor

Anchors are used to transmit the loads (reactions) from the curtain wall load-bearing structure to the main building structure. The Anchors can be either cast-in or post-installed anchorages. The following are some of the major anchor types used in curtain wall construction.

2.2.5.1 Cast-in anchors

Cast-in anchors are anchors that are placed and held in position before concrete casting. The anchors are embedded inside the concrete structure ready to accept the brackets. The commonly used embedment systems are the *embedded steel plate system* and the *cast-in channel system. W*hile using the *embedded steel plate system*, the brackets used for holding the load-bearing structural elements of the façade, are going to be welded to the embedded steel plate.

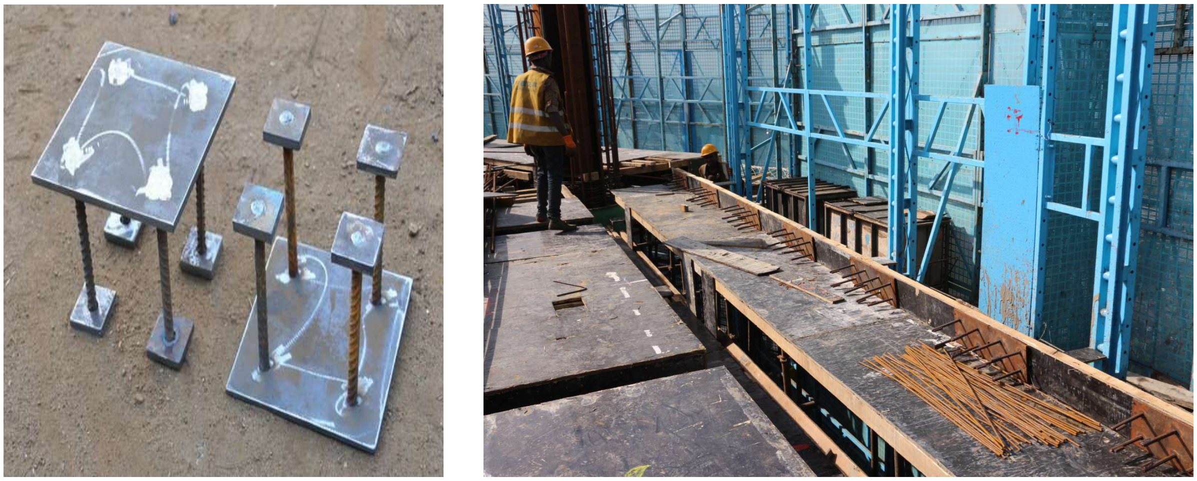


Figure 2-25: Steel plate embedment for curtain wall

Whereas in the *cast-in channel system*, the brackets are bolted to the embedded channel using special T-shaped bolts. The channels can be embedded on the top of the slab or the side of the slab considering the type of brackets used. The cast-in channel embedded on the edge of the slab is suitable for the Stick-built curtain wall system whereas the channels embedded on top of the slab are suitable and broadly used for unitized curtain wall application as shown in Figure 2-26.

Figure 2-26: Top cast-in channel (left) and edge cast-in channel (right)

2.2.5.2 Post-installed Anchors

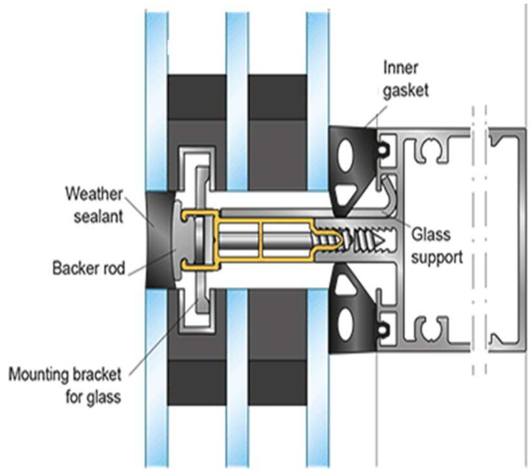
In this system, the brackets are attached to the supporting concrete structure by using expandable anchor bolts by first drilling the concrete structure to the required size and depth. Chemical anchor bolts are also available on the market.

Figure 2-27: Anchor bolt anchoring system

2.2.6 Weather Sealants and gaskets

Curtain walls have different components and members attached using connectors. In such connections, there will be some gaps and holes which need to be sealed to control water and air leakage. On the other hand, gaps between the glazing panel and the aluminum frames that are left to avoid direct contact between them must be sealed by allowing some tolerance for thermal movement.

To fill the gaps while giving some movement tolerances, a material with elastic property having good water and air barrier property needs to be used. Silicone sealants and rubber gaskets are an excellent choice as a filler to seal the gap while giving the freedom for movement.



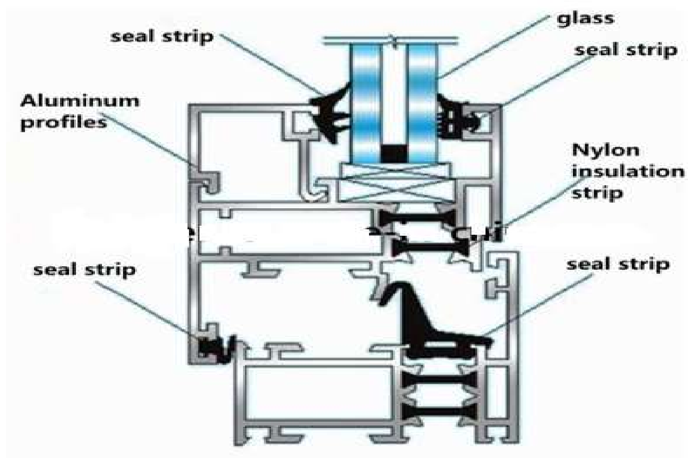


Figure 2-28: Weather sealant and gasket

2.3 Curtain wall materials

A curtain wall is not a monolithic wall rather it comprises different types of materials with different physical and mechanical properties assembled to make a single wall. Usually, both stick-built and unitized curtain walls utilize Aluminum profiles as a load-bearing frame, glass as an infill, stainless steel fasteners, and silicone as a sealant. Before discussing about curtain wall, one must have at least the basic know-how about these materials. The following are some of the basic materials used for curtain wall construction.

2.3.1 Aluminum

Aluminum is a silver-white metal element obtained from its chief ore **bauxite**; a rock composed of more than 50% aluminum hydroxides formed by weathering in tropical regions. Aluminum is the earth's third most abundant element (after oxygen and silicon) and the most abundant metal in the earth's crust (EN1999 for Standardization, 2004).

Extruded Aluminum alloy profiles are being used as a building construction material by replacing steel in some structural applications including curtain walls. The main advantages of Aluminum over steel as a building construction material relies on its corrosion resistance, its lightness, and its extrudability to any desired shape, and its 100% recyclability.

2.3.1.1 Aluminum alloys

Aluminum is not just one material, but it gives rise to a family of different groups of alloys whose mechanical properties widely vary from one group to another and also within each group.

Aluminum alloys are alloys (a combination of metals or metal and another element) in which Aluminum (Al) is the predominant metal. These alloys are grouped into two categories as follows:

A. wrought alloy
B. cast alloy

2.3.1.1.1 Wrought alloy

wrought alloys are alloys that are ductile enough to be hot or cold worked, while in solid-state, to shape during fabrication.

From the technological use, the **wrought** aluminum alloys can be grouped into eight series, according to the American Association classification, the first of the four digits (**X**xxx) characterizing the main alloying element and the other three the secondary ones (EN1999 for Standardization, 2004). The second digit (x**X**xx) denotes a modification of an alloy. For example, 6463 is a modification of 6063 with slightly more restrictive limits on certain alloying elements, such as iron, manganese, and chromium, to obtain better finishing characteristics. The Association sequentially assigns the last two digits (xx**XX**) (Kissell & Ferry, 2002).

Wrought Alloys are divided into two groups based on whether or not their strengths can be increased by heat treatment. Both ***heat treatable*** and ***non-heat-treatable*** alloys can be strengthened by strain hardening, which is also called cold-working. The alloys that are not heat-treatable may only be strengthened by cold-working. Whether or not an alloy is heat treatable depends on its alloying elements (Kissell & Ferry, 2002).

- ✓ ***Heat-treatable alloys*****:** are capable of being strengthened by suitable thermal treatment
- ✓ ***non-heat-treatable alloys:*** cannot be strengthened substantially by thermal treatment. Their basic strength is determined by the alloying content, but can be increased significantly by work-hardening and in some cases also by grain size refinement.

Table 2-2: Aluminum wrought alloy designation

No.	Alloy group ID	Alloy Elements	Characteristics				Heat treatment
			Structure type	Form	Application	Properties	
1	**1000 Series**	Pure Aluminum	in low stressed structures	plate	Electrical and chemical industries for cables and tanks	Excellent corrosion resistance	Non-heat-treatable
2	**2000 Series**	Aluminum and Copper	not popular in structural engineering	profiles, plates, and pipes	aeronautical industry with riveted connections	bad weldability and its corrosion resistance is not very high	Heat-treatable
3	**3000 Series**	Aluminum and Manganese		Panel	panels and trapezoidal sheeting for roofing systems	Slightly higher strength than pure Aluminum with very high ductility.	non-heat treatable
4	**4000 Series**	Aluminum and Silicone			for welding wires	Similar to 3000 serious.	Varies by alloy
5	**5000 Series**	Aluminum and Magnesium	used for welded structures		in marine environment	High corrosion resistance, good strength	Non-heat-treatable
6	**6000 Series**	Aluminum, Silicone and Magnesium	welded, bolted or riveted connections	suitable for extrusion, but also rolled and tubes	used for structural members and for building façade, van bodies, boat masts, scaffolds, cranes, etc.	good corrosion resistance, extrudability, machinability, weldability and strength, excellent ability to be anodized	Heat-treatable
7	**7000 Series**	Aluminum and Zinc		both extruded and rolled	automotive, bumpers, etc.	High strength and toughness,	Heat-treatable
8	**8000 Series**	Aluminum, Iron and Silicone				packaging and building industry	

Among the above-listed groups, **6000 series** aluminum alloys are preferable and widely used for building façade and window-door applications due to their good strength combined with good corrosion resistance, ease of formability, easily extruded to any forms, and shapes, and excellent ability to be anodized. Among the alloys in this group 6060, 6061, 6063, and 6082 are commonly used for building façade applications.

2.3.1.1.2 Cast alloy

Cast alloys are those alloys that are poured in a molten state into a mold that determines their shape. This process is useful for forming complex three-dimensional shapes, but it suffers some limitations for structural uses. Most castings have more variation in mechanical properties and less ductility than wrought aluminum alloys. This is due to defects that are inherent to the casting process, such as porosity and oxide inclusions, and the variation in cooling rates within a casting (Kissell & Ferry, 2002).

The cast alloy designation system is based on a 3 digit-plus decimal designation xxx.x (i.e. 356.0). The first digit (**X**xx.x) indicates the principal alloying element, which has been added to the aluminum alloy (see the table below). The second and third digits (x**XX**.x) are arbitrary numbers given to identify a specific alloy in the series. The number following the decimal point indicates whether the alloy is a casting (.0) or an ingot (.1 or .2). A capital letter prefix indicates a modification to a specific alloy.

Table 2-3: Cast Aluminum alloy designation System

Alloy Series	Principal Alloying Element
1xx.x	99.000% minimum Aluminum
2xx.x	Copper
3xx.x	Silicon Plus Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

2.3.1.2 Tempers

Tempering refers to the alteration of the mechanical properties of a metal employing either a mechanical or thermal treatment. Aluminum alloys are tempered by heat-treating or strain hardening to further increase strength beyond the strengthening effect of adding alloying elements. Before tempering, alloys begin in the annealed condition, the weakest but most ductile condition.

Whereas after tempering, while increasing the strength, decreases ductility and, therefore, decreases workability (Kissell & Ferry, 2002).

For the standard temper designations, the following definitions are applied as per the European Aluminum Association automotive manual.

Table 2-4: Aluminum temper types

Tempers	Description
Cold working	Plastic deformation of a metal at such temperature and rate that strain-hardening occurs.
Strain-hardening	Modification of a metal structure by cold working resulting in an increase in strength and hardness with loss of ductility.
Solution heat-treating	A thermal treatment consists of heating the products to a suitable temperature, holding at that temperature long enough to allow constituents to enter solid solution, and cooling rapidly enough to hold the constituents in solution.
Aging	Precipitation from supersaturated solid solution resulting in a change in properties of an alloy, usually occurring slowly at room temperature (*natural aging*) and more rapidly at elevated temperatures (*artificial aging*).
Annealing	A thermal treatment to soften metal by removal of strain-hardening or by merging precipitates from solid solution.

The basic temper designations used are summarized in Table 2-5.

Table 2-5: Aluminum temper designations

Letter	Description
F	***As fabricated*** – Applies to products of a forming process in which no special control over thermal or strain hardening conditions is employed
O	***Annealed*** – Applies to product which has been heated to produce the lowest strength condition to improve ductility and dimensional stability
H	***Strain Hardened*** (wrought products only) –Applies to products that are strengthened through cold-working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The “H” is always followed by two or more digits like H1, H2…
W	***Solution Heat-Treated*** – An unstable temper applicable only to alloys which age spontaneously at room temperature after solution heat-treatment
T	***Thermally Treated*** - To produce stable tempers other than F, O, or H. Applies to product that has been heat-treated, sometimes with supplementary strain-hardening, to produce a stable temper. The “T” is always followed by one or more digits

For thermally treated tempers [T], the numbers 1 through 10 following the ‘‘**T**’’ are used as shown below. For the alloys used on façade applications, **T5** and **T6** tempers are the most commonly used.

Table 2-6: Common thermally treated tempers of aluminum for building façade application

Temper	Description
T4	Solution heat-treated and naturally aged to a substantially stable condition
T5	Cooled from an elevated temperature shaping process and then artificially aged ✓ Applies to products that are not cold-worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits, for example, 6063-T5 extrusions.
T6	Solution heat-treated and then artificially aged ✓ Applies to products that are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits, for example, 6063-T6 extrusions.

2.3.1.3 Product forms

Aluminum alloys are produced in many forms like extrusion, flat-rolled products, castings, and forgings. Except casting, which is typically a casting alloy product, the other forms of Aluminum products are done on wrought Aluminum alloys. Castings typically have less reliable properties than the wrought product forms, and forgings are often more expensive to produce than other wrought forms. Castings and forgings do, however, lend themselves to more complex shapes than extrusions and flat-rolled products (Kissell & Ferry, 2002).

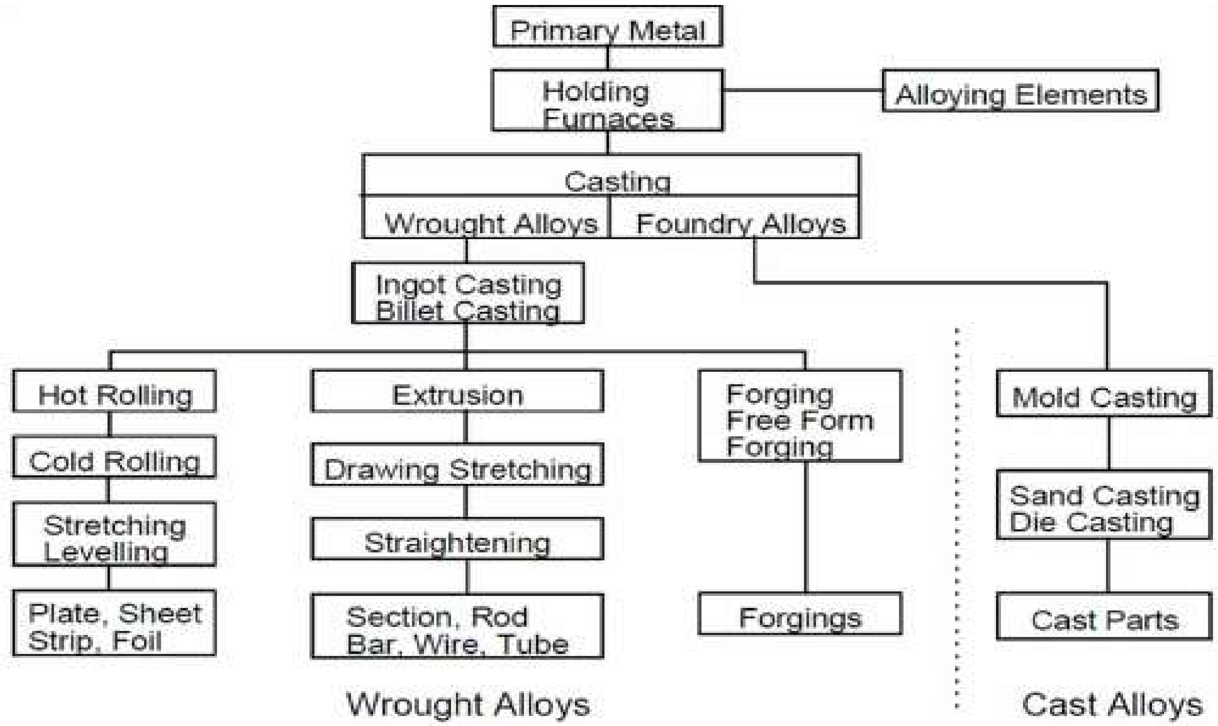


Figure 2-29: Aluminum product forms

2.3.1.3.1 Extrusion process

Extrusion is a process of pushing solid material through an opening called a die to form parts with complex cross-sections. The extrusion process makes aluminum an extremely versatile material for structural design. Rather than being limited to the standard rolled shapes, designers can create their cross-sections, putting material where it is needed. Solid and hollow cross-sections, even sections with multiple hollows, can be readily extruded (Kissell & Ferry, 2002). The extrusion process also allows us to produce and incorporate interlocking sections, screw chases, gasket retaining grooves, etc. on the profile.

Five extrusion processes are being practiced in the industry. These are the direct extrusion process, indirect extrusion process, impact extrusion process, Hydrostatic Extrusion process, and tube extrusion process. The direct extrusion process is the most commonly practiced.

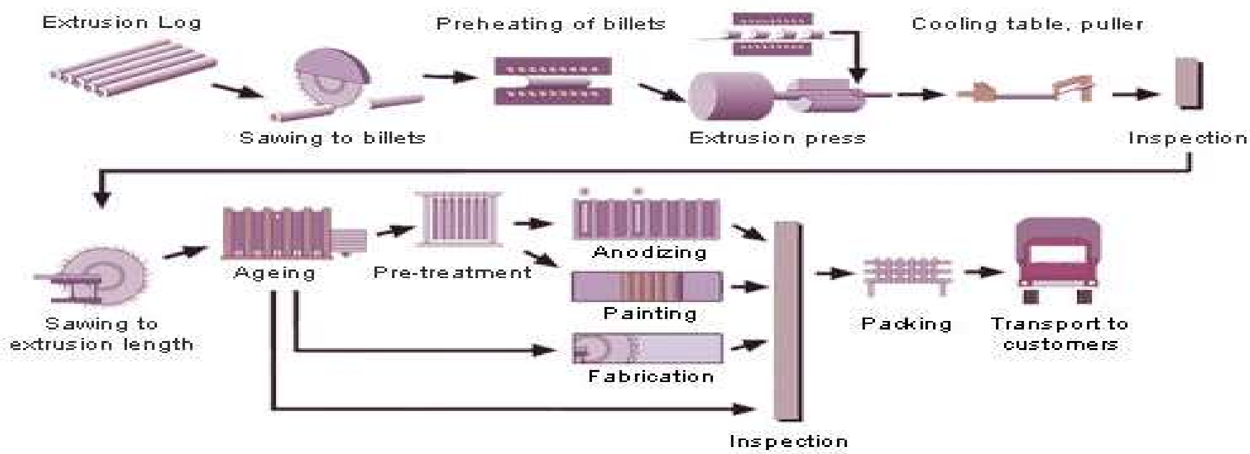


Figure 2-30: Direct extrusion process

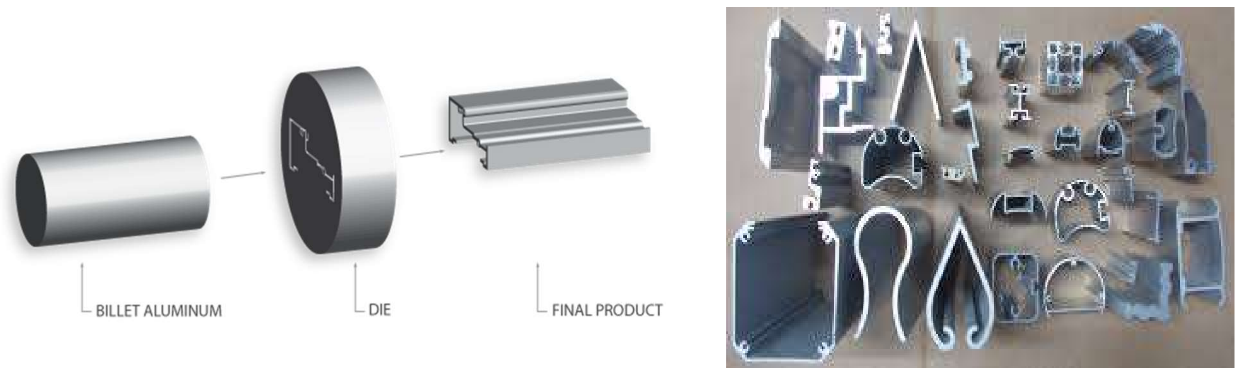


Figure 2-31: Extruded profiles

2.3.1.4 Coatings and surface finishes

Extruded aluminum is particularly receptive to high-performance architectural coatings to ensure a maintenance-free performance and longer service life. A variety of finishes are available for aluminum with a customized look and limitless color choices. Factors in the selection of the type of finish are cost, appearance, and durability. Common finishes include ***mill finish*** (bare aluminum), ***anodizing***, ***painting***, ***powder coating,*** and ***mechanical finishes***.

2.3.1.4.1 Mill finish (bare aluminum)

The Aluminum Association publication Specifications for Aluminum plate Metal Work in Building Construction states:

''One of aluminum's most useful characteristics is its tendency to develop an extremely thin, tough, invisible oxide coating on its surface immediately on exposure to air. This oxide film, although

only 2 to 4 ten-millionths of an inch thick on first forming, is almost completely impermeable and highly resistant to attack by corroding atmospheres.''

This aluminum-oxide film of mill finish does not weather away or stain adjacent materials.

Figure 2-32: Aluminum mill finish surface

2.3.1.4.2 Anodized finish

Anodizing is a process that accelerates the formation of the oxide coating on the surface of aluminum, producing a thicker oxide layer than would occur naturally. An anodized coating is part of the metal, and so has excellent durability. One of the primary advantages of anodizing is its resistance to abrasion. The color, however, depends on the alloying elements and, thus, varies among different alloys and even among parts of the same alloy due to non-uniform mixing of alloying elements (Kissell & Ferry, 2002).

Figure 2-33: Aluminum anodizing process

2.3.1.4.3 Painted finish

Coatings based on polyvinylidene fluoride (PVDF) resins have become the standard for architectural applications of painted aluminum. These products are chemically inert and exhibit excellent weatherability. Painting is sometimes considered to be a method of isolating aluminum from dissimilar materials.

These products vary in availability and cost but are typically more expensive than anodizing when applied to fabricated assemblies. As with any coating application, the preparation of the substrate is critical (Kissell & Ferry, 2002).

2.3.1.4.4 Powder coating finish

Powder coating is an advanced method of applying a decorative and protective finish to aluminum. The process results in a uniform, high quality, and attractive finish.

The pre-treated aluminum components are racked to a conveyor, which is earthed. A powder spray gun is set to produce a cloud of powder particles with a strong electrostatic charge. The charged particles are attracted through the electrostatic field to the face of the product and the sides and back along the lines of force in the electrostatic field. After the powder has been applied, the coating is put on the stove at temperatures specified by the powder manufacturer.

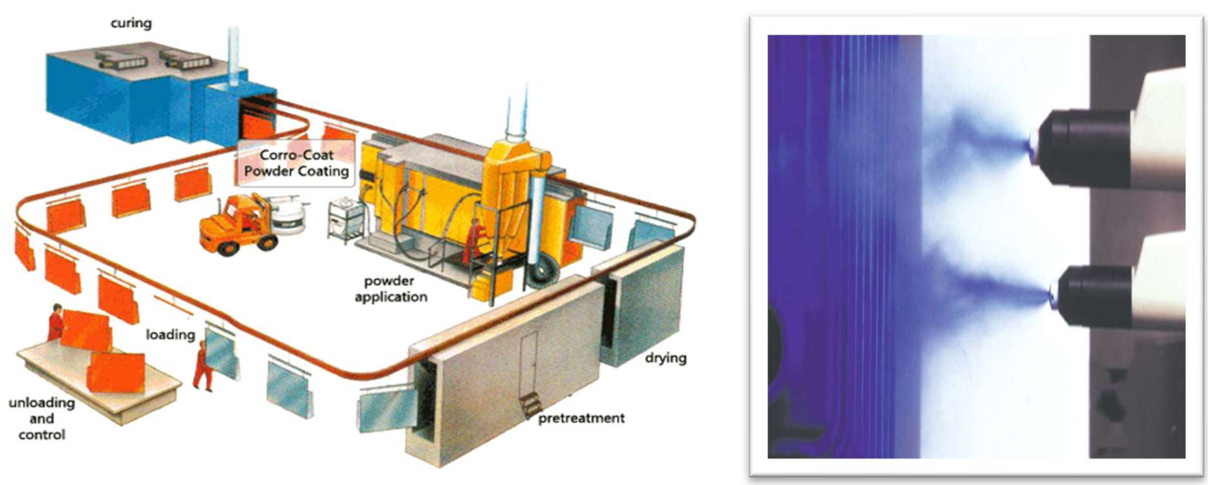


Figure 2-34:Powder coat finishing process

Powder-coated surfaces are more resistant to chipping, scratching, fading, and wearing than other finishes. Color selection is virtually unlimited with high and low gloss, metallic and clear finishes available. And colors stay bright and vibrant. Texture selections range from smooth surfaces to a wrinkled or matt finish and rough textures designed for hiding surface imperfections.

2.3.1.5 Physical properties of Aluminum

2.3.1.5.1 Density

Aluminum is known for its lightweight characteristics. It has an atomic weight of 26.98 (g/mol) and a specific gravity of 2.70, approximately one-third the weight of steel or copper. The resultant high strength to weight ratio makes it an important structural material.

2.3.1.5.2 Strength

Pure aluminum doesn't have a high tensile strength. However, the addition of alloying elements like manganese, silicon, copper, and magnesium can increase the strength properties of aluminum and produce an alloy with properties tailored to particular applications (www.aalco.co.uk).

2.3.1.5.3 Corrosion resistance

When exposed to air, a layer of aluminum oxide forms almost instantaneously on the surface of aluminum. This layer has excellent corrosion resistance. It is fairly resistant to most acids but less resistant to alkalis.

2.3.2 Glass

Glass is a hard, brittle, amorphous (non-crystalline) substance, typically transparent or translucent, made by fusing sand with soda and lime. Generally, glass forms when a liquid is cooled down in such a way that "freezing" happens instead of crystallization. Glasses do not consist of a geometrically regular network of crystals, but of an irregular network of silicon and oxygen atoms with alkaline parts in between. The most common oxide glass, silica-soda-lime glass, is used to produce glazing (Fröling, 2013).

The glass used for window and curtain wall glazing is float glass. Float glass is a sheet of glass made by floating molten glass on a bed of molten metal, typically tin, which gives the sheet uniform thickness and very flat surfaces.

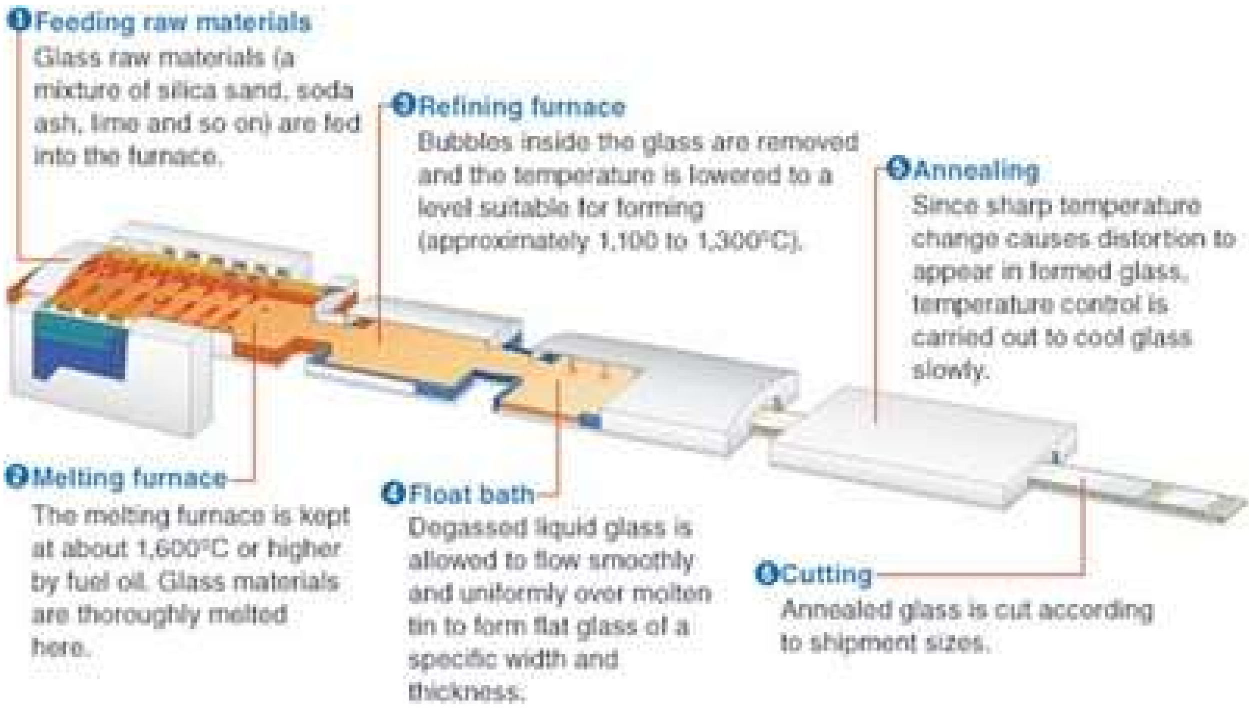


Figure 2-35:Float glass production process

2.3.2.1 Types of glass

Float glasses are used to produce different types of glasses for architectural use. During the post-processing phase, using different methods, many types of glasses with different properties and performances can be manufactured. The techniques usually involve heating and cooling the manufactured float glass or bonding them together in different ways.

The selection of which glass type to use for every kind of façade depends on the specific structural and functional performance requirements. Although there are many types of glasses, the most common ones are described below.

2.3.2.1.1 Annealed Glass

Annealing is a process of slowly cooling float glass to relieve the internal stresses after it is formed. The glass, traditionally annealed on shelves in a melting furnace, is now usually carried on rollers through a temperature-controlled kiln known as a **Lehr** or annealing ovens (www.glazette.com).

Annealed glass is a standard sheet of float glass where the glass splits into larger fragments during breakage. Glass that has not been properly annealed retains thermal stresses caused by quenching, which indefinitely decreases the strength and reliability of the product. Inadequately annealed glass is likely to crack or shatter when subjected to relatively small temperature changes or mechanical shock or stress and it may even fail spontaneously.

2.3.2.1.2 Fully tempered (toughened) Glass

During tempering, float glass is heated above its transition temperature of 564 °C (1,047 °F) to around 620 °C (1,148 °F). The glass is then rapidly cooled (quenched) with forced air drafts while the inner portion remains free to flow for a short time.

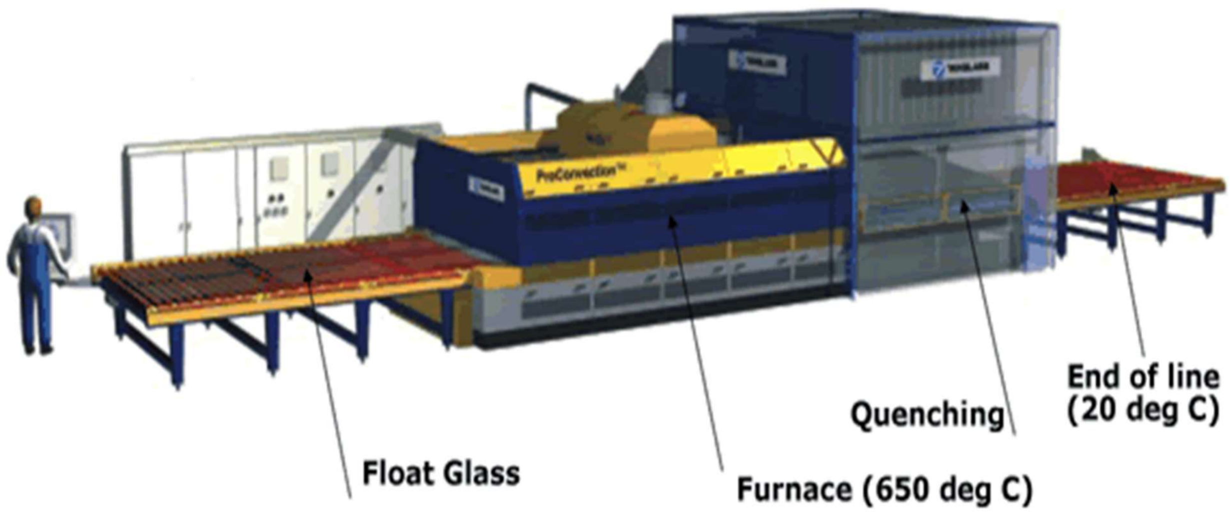


Figure 2-36: Tempered glass production process

The tempering process aims to create a parabolic residual stress field in the thickness direction that has tensile stresses in the core and compressive stresses at the surfaces of the glass. Fully tempered glass usually breaks into small harmless pieces and therefore fully tempered glass is also termed as safety glass.

Fully tempered glass is four times (4x) as tough as annealed glass of the same thickness and size. It is not harder or softer than annealed glass but is tougher. Tempered glass has also higher thermal strength, and it can withstand high-temperature changes up to 250°C.

All production processes of the glass such as cutting to size, edge polishing, and drilling must be done before tempering. The tempering process does not affect the color, clarity, chemical composition and light transmission of the glass also it has a drawback of high optical (visual) distortions.

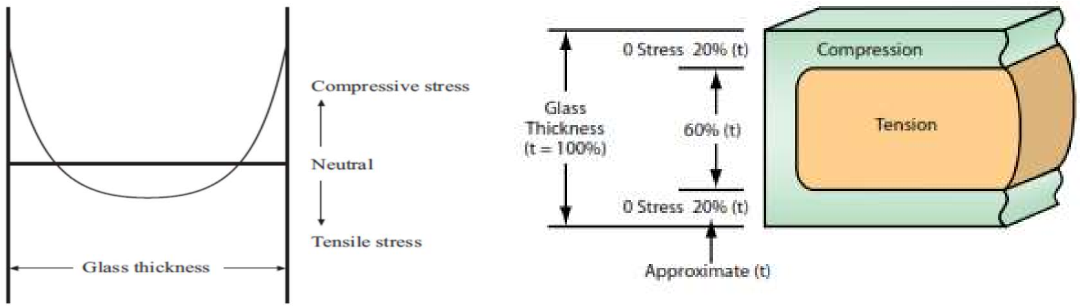


Figure 2-37: The residual stress profile in a tempered glass and Stress profile of the toughened glass

2.3.2.1.3 Heat-strengthened glass

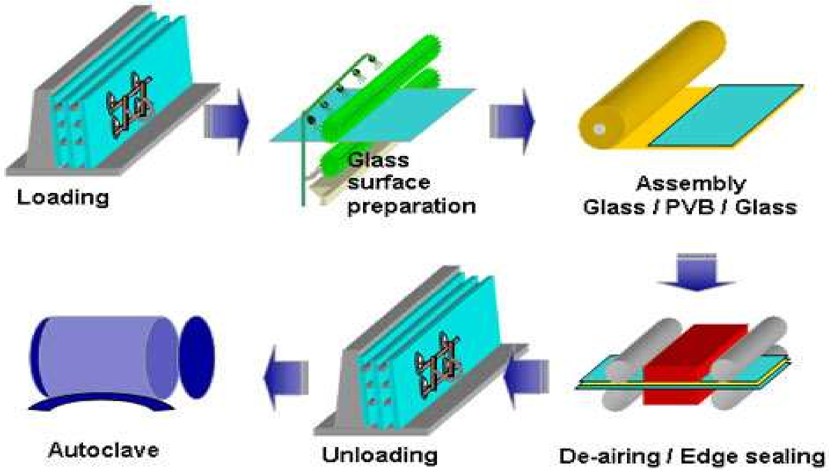
Heat-strengthened glass is produced similarly to fully tempered glass, but the cooling rate is slower. The resulting residual stress is lower, and thus the tensile strength is lower than for fully tempered glass. At fracture, the fragments are larger than the fully tempered glass and it is not considered as safety glass. On the other hand, the larger glass fragments can allow for a greater post-breakage load capacity in compression than for fully tempered glass (Fröling, 2013)

This glass is twice (2x) stronger than standard annealed float glass but not as strong as tempered glass. It is a good compromise when there is a possibility of breakage but life safety is not an issue and also results in a façade having fewer optical distortions.

2.3.2.1.4 Laminated Glass

Laminated glass consists of two or more glass panes bonded by a plastic interlayer. The use of laminated glass in architectural glazing is of great advantage for two reasons. First, if one glass pane breaks, the remaining panes can continue to carry the applied loads given that each glass lite is properly designed. Secondly, the scattered glass pieces can stick to the interlayer and thereby serve to prevent people from getting injured.

This glass type is preferred for structural glass applications with different combinations of glasses for different purposes. Blast resisting, bulletproof, structural glass elements like structural facades, glass column, beam, and staircase are being used due to the advancement of laminated glasses.



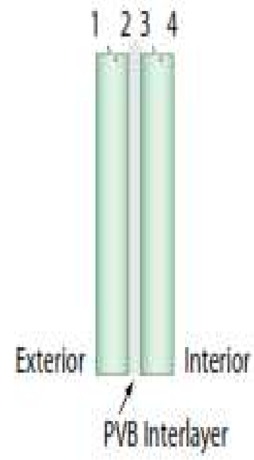


Figure 2-38: Laminated glass production process(left) (www.glazette.com website) and laminated glass (right)

The widely used and suitable for the application is the interlayer PVB (polyvinyl butyral). Interlayer chemistry progressed from ***cellulose nitrate*** to ***cellulose acetate*** and then to ***PVB*** plasticized interlayer which was honored in 1938 as a major technological achievement. The current major interlayer development for laminated glass by DuPont in 1998 was ***SentryGlas®*** an Ionoplast structural interlayer. SentryGlas® interlayers are five times (5x) stronger and up to 100 times stiffer than conventional laminating materials. With this kind of strength, SentryGlas® interlayers create stronger laminated glass that protects against storms, impacts, and powerful blasts (www.dupont.com).

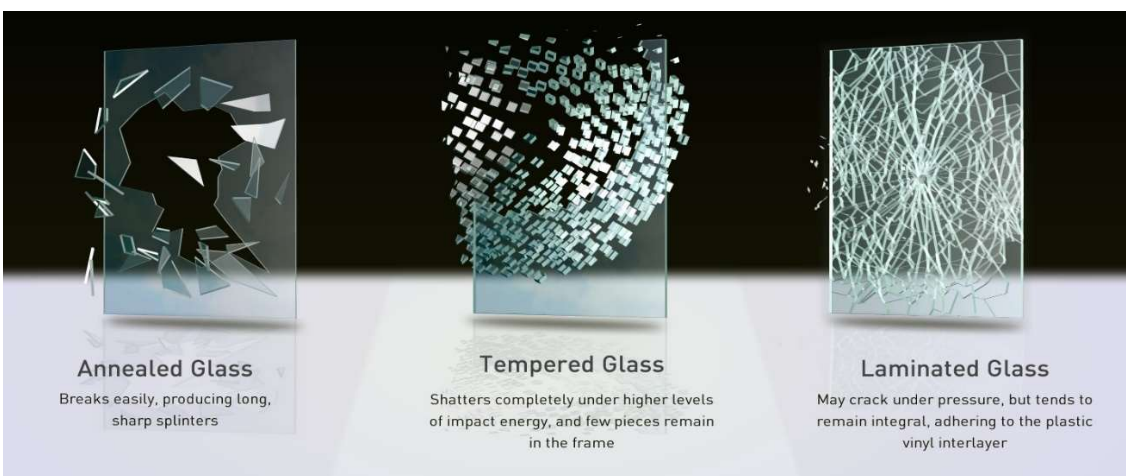


Figure 2-39: Breakage pattern of Annealed, tempered, and laminated glass

2.3.2.1.5 Insulated Glass Unit (IGU)

Insulated Glass, often called double glazing, is a combination of two or more panes of glass spaced apart with a spacer bar and hermetically sealed with a primary and secondary sealant to form a single unit with one or more air spaces in between.

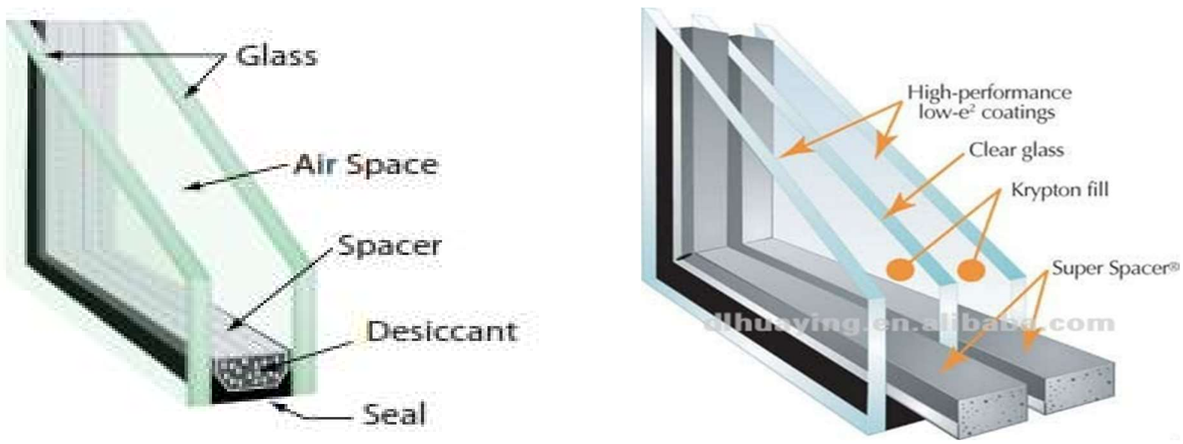


Figure 2-40: Double glazed (left-hand side) and triple glazed (right-hand side) Insulating glass units (IGU)

IGU glasses also improve the thermal performance, thus significantly reducing heating and air-conditioning costs. When used in conjunction with low emissivity and/or reflective glass coatings, IG units become effective means to conserve energy and comply with energy regulations. It also reduces intermediate condensation in cold climates, and increase comfort near windows, thus maximizing the usable interior space (www.glazettee.com). Insulated glasses are also used for their sound insulation advantages.

The gap (cavity) in-between the two glass panes are commonly be filled with Dry Air or Vacuum sealed. However, the use of Argon gas, Krypton gas, etc. is also being used where better thermal performance is crucial for the curtain wall glazing.

2.3.2.1.6 Wired glass

Wired glass is annealed glass with an encapsulated steel wire mesh. The presence of the wire mesh is believed to be a strengthening component, as it is metallic, and conjures up the idea of rebar in reinforced concrete while, wired glass is weaker than unwired glass due to the incursions of the wire into the structure of the glass.

Depending on the weight of the mesh, wired glass can be used as fire-resistant or safety glass. In recent years, new materials (laminated glass) have become available that offer both fire and safety ratings resulting in debate for the continued use of wired glass as a safety glass worldwide. The wire prevents the glass from falling out of the frame even if it cracks under thermal stress, and is far more heat-resistant than a laminating material.

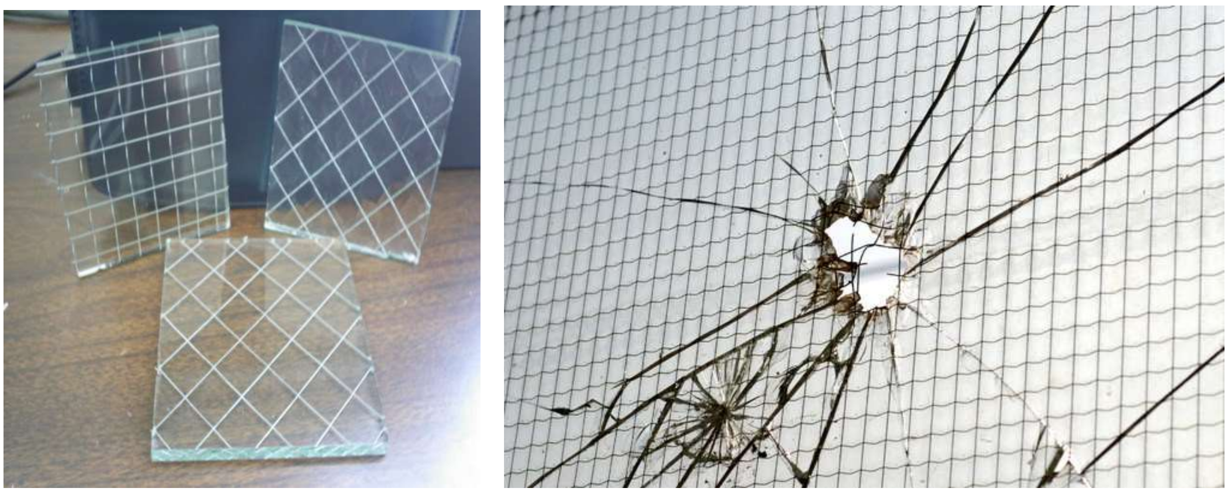


Figure 2-41: Wired glass

2.3.2.2 Glass coloring and surface treatment

Float glasses are colored or surface treated for decorative or performance requirements. Glasses can be produced with different colors, textures, transparency, and energy efficiency. The following are some of the glass types treated using the aforementioned systems.

2.3.2.2.1 Clear and ultra-clear glass

Although the name clear glass might indicate the glass being clear, the glass is greener while looking at it at the edge of a green hue present in it. The green color becomes more visible especially when the glass thickness increases. The presence of iron in the glass is the reason behind the green color of clear glass.

Removing or reducing the content of Iron in the clear glass reduces the green color of the glass. These glasses are termed ultra-clear glass or, usually referred to as, Low-Iron clear glass.

Figure 2-42: Clear vs ultra-clear glass

2.3.2.2.2 Frosted glass

Frosted glass is produced by sandblasting or acid etching of a clear glass sheet creating a pitted surface on one or both sides of the glass pane. The process could be either by physically scratching the glass using rough materials /like sand/ or by simply using some chemicals which will create a blurred vision type of glass while at the same time transmitting light.

Sandblasting involves corroding glass by violently projecting sand upon its surface through a current of air or steam. The outputting glass surface will have a rough texture and a blurred vision.

On the other hand, during acid etching, the glass surface (one side) is treated with hydrofluoric acid, gaining a uniformly smooth and satin-like appearance, with a translucent effect. Different designs on the glass surface can be printed by using stencils.

Figure 2-43: Sandblasted glass (on the left-hand side) and acid-etched glass (on the right-hand side)

2.3.2.2.3 Enamel or screen-printed glass

Enameled or ceramic frit colored glass is a process of applying enamels through painting on the glass and letting it cure on the glass by using heat. Enamels are an opaque or semi-transparent glossy substance, usually soft powdered colored glass that are mixed well and painted onto the glass. The enamels might comprise 70-95% of glass powder and 5-30% pigments.

Enameled glass is tempered or heat-strengthened glass, as the paint curing by heat after the painting is a must. In addition to its decorative function, enameled glass is also a solar ray controller.

Figure 2-44:Enameled (color painted) glass

2.3.2.2.4 Body-tinted glass

Body-tinted glass is a normal float glass where the glass colorants and Iron are added during float glass manufacturing to produce tinted glass. Colored glasses have both aesthetical and performance advantages over clear glass. The different types of glass tint colors can be achieved by using different colorant additives. For instance, when using iron, the colors green, brown, and blue can be achieved and while using copper the colors green, blue, and red can be gain.

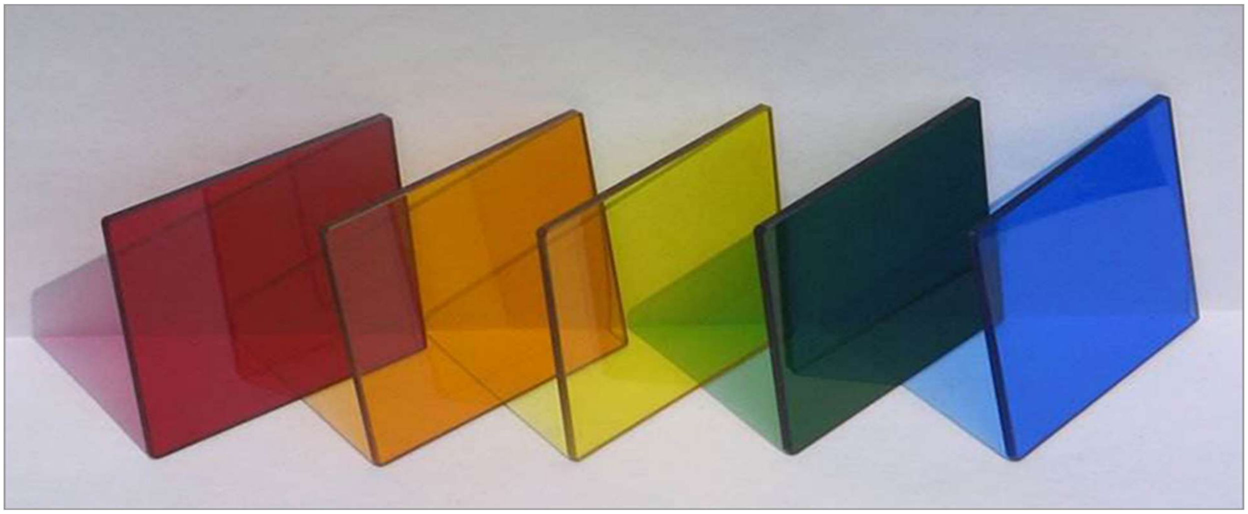


Figure 2-45: Body-tinted glass

The added colorant additives don't affect the basic molecular arrangement of the glass. However, it enhances the energy-saving capability by reducing the solar heat penetration into the building. The thermal performance values of a tinted glass are different based on the attained glass color (www.glazette.com). Although the color is homogenous throughout the glass thickness, but matching the exact colors in different batches of production is very much difficult.

2.3.2.2.5 Reflective glass

Reflective glass is a type of float glass where the visible light of the solar spectrum is reflected by the metallic coating applied on the glass. The reflection extent is different depending on the type of coating and the number of coatings applied. Reflective glasses have a mirror effect from one side as it blocks visibility on one side and allow vision on the other.

Figure 2-46: Reflective glass curtain walls

The two ways of reflective glass manufacturing processes are the pyrolytic process and vacuum (magnetron) process.

1. Production Pyrolytic (On-line) process:

During the float glass production process, the semi-conducted metal oxide is directly applied to produce a reflective coating on the glass. This on-line process is done while the glass is still hot and before annealing. The coating is fused to the glass at 1200° C and the resulting coating is hard and durable coating.

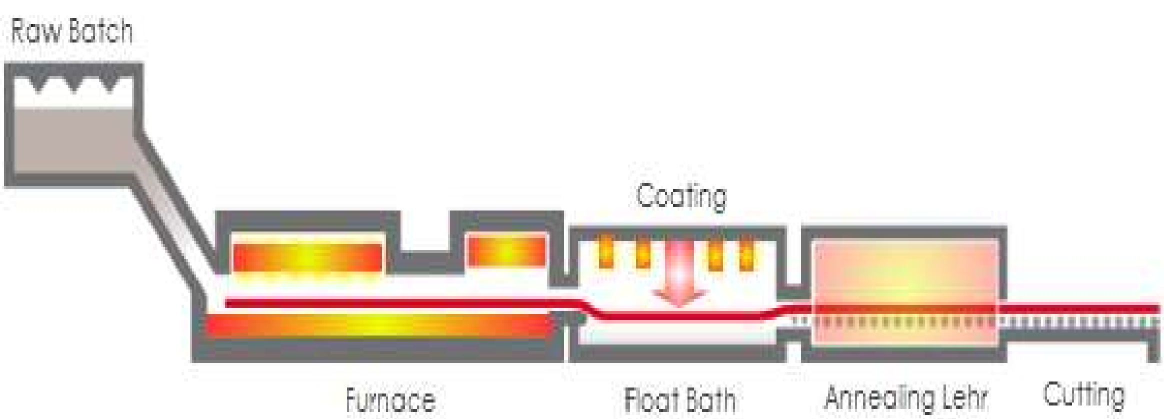


Figure 2-47: Pyrolytic glass coating process

2. Vacuum (Magnetron) Process (Off-line):

When the reflective metal oxide coating is applied to the finished glass it is termed as a vacuum (off-line) process. The resulting coating is soft and it might easily be damaged and require protection from the external environment. Consequently, it is termed as the soft coating. It is highly advisable to use coated glasses with this process in IGU glasses instead of single-layer glazing. For thermally toughened (tempered and heat-strengthened) glasses, the coating must be applied after glass toughening is finished (www.glazette.com).

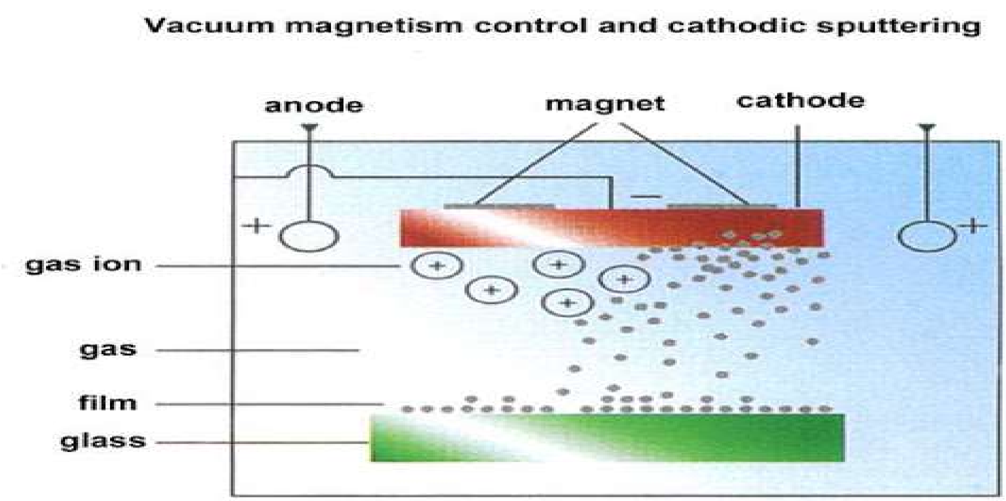


Figure 2-48: Vacuum (Magnetron) glass coating Process

2.3.2.2.6 Low-Emissivity (Low-E) glass

Low-E glasses are glasses coated with an extremely thin, nearly invisible film of metal or metal oxide layers which will reduce the thermal transmittance through the glass by restricting the infrared (radiative) spectrum of the sunlight. For the energy conservative design of glazing, the usage of such types of glass coatings is very much significant. When using Low-E coated glass in IGU, the thermal control, and energy efficiency of the glass will greatly enhance.

There are two different types of Low-E coatings: passive Low-E coatings and solar control Low-E coatings:

Passive Low-E coatings: are designed to increase solar heat gain into the building to create the effect of “passive” heating and reducing reliance on artificial heating.

Solar control Low-E coatings: are designed to limit the amount of solar heat that passes into the building and to keep it cooler and reducing energy consumption related to air conditioning.

The Low-E coatings can be applied by either pyrolytic (on-line) or Magnetron Sputter Vacuum Deposition (MSVD) similarly with the reflective glass coating process.

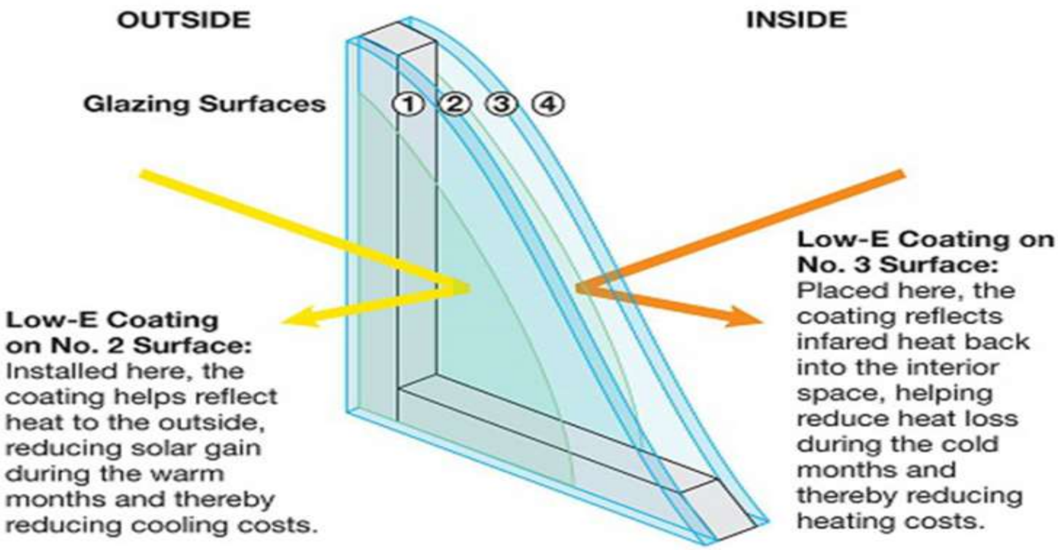


Figure 2-49: Low-E coated IGU glass

2.3.2.3 Physical properties of glass

The following are the Physical properties of glass based on the manual of Saint-Gobain

2.3.2.3.1 Density

The density of glass is 2,500 kg per m^3, which gives flat glass a mass of 2.5 kg per m^2 per mm of thickness.

2.3.2.3.2 Compressive strength

The compressive strength of glass is extremely high: 1,000 N/mm2 = 1,000 MPa. This means that to shatter a 1cm cube of glass, it requires a load of some 10 tons. However, due to the surface flaws or imperfections on glass and due to its high brittle nature, the strength of glass considered for design is very much lower.

2.3.2.3.3 Tensile strength

When glass is deflected, it has one face under compression and the other in tension. Whilst the resistance of glass to compressive stress is extremely high, its resistance to tensile stress is significantly lower. The resistance to breakage on deflection is in the order of:

- ✓ 40 MPa (N/mm2) for annealed glass
- ✓ 70 MPa for heat-strengthened glass
- ✓ 120 to 200 MPa for tempered glass (depending on thickness, edgework, holes, notches, etc).

2.3.2.3.4 Elasticity

Glass is a perfectly elastic material: it does not exhibit permanent deformation, until breakage. However, it is fragile (brittle), and will break without warning if subjected to excessive stress. In its rigid state, glass can be regarded as an "amorphous solid". Because of this, the mechanical behavior of glass is very brittle without any plastic deformation capacity. Under loading, the strain response to the stress is perfectly linear with sudden failure.

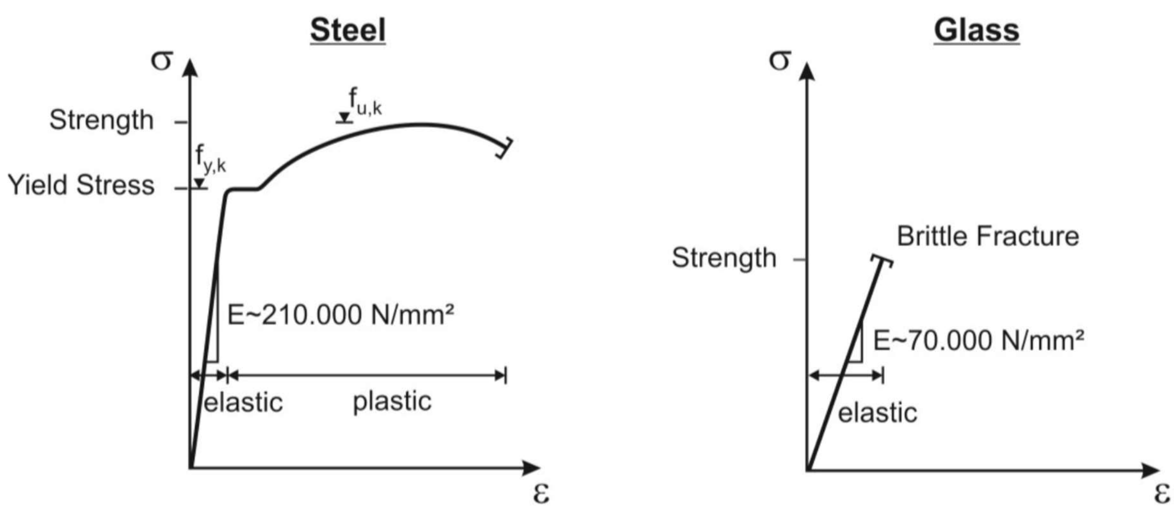


Figure 2-50: Stress-strain relation of glass and steel

2.3.2.3.5 Thermal linear expansion

Linear expansion is expressed by a coefficient measuring the stretch per unit length for a variation of 1°C. This coefficient is generally given for a temperature range of 20 to 300 °C. The coefficient of linear expansion for glass is 9 x 10^{-6} m/mk.

2.3.2.3.6 Thermal stress

Due to the low thermal conductivity of glass, partially heating or cooling a sheet of glass creates stresses which may cause thermal breakage. When glass is framed, the edges are encased in the rebate, which protects them from direct solar radiant heat. This can cause temperature differentials sufficient to cause thermal breakage. This risk is increased where heat absorbent solar control glasses are used.

2.3.2.4 Spontaneous breakage of glass

Glass could break sometimes without any obvious cause termed as spontaneous breakage. This problem might be caused by the existence of some impurities in the glass during float glass manufacturing. One of the well-known impurities of glass is the *Nickel Sulfide (NiS) inclusions* formed when nickel-rich contaminants combine with Sulphur.

Although Nickel sulfide inclusion exists in all float glasses, it causes spontaneous breakage in tempered glass mostly. The Nickel Sulfide stones that were formed during the production of float glass due to nickel contamination, can end up in the center tension zone of tempered glass while glass tempering. When the glass becomes exposed to varying temperatures, the tiny Nickel Sulfide stone may grow in size and volume triggering the glass to unleash all the stored energy on the tension zone at once and causing spontaneous breakage with a butterfly pattern.

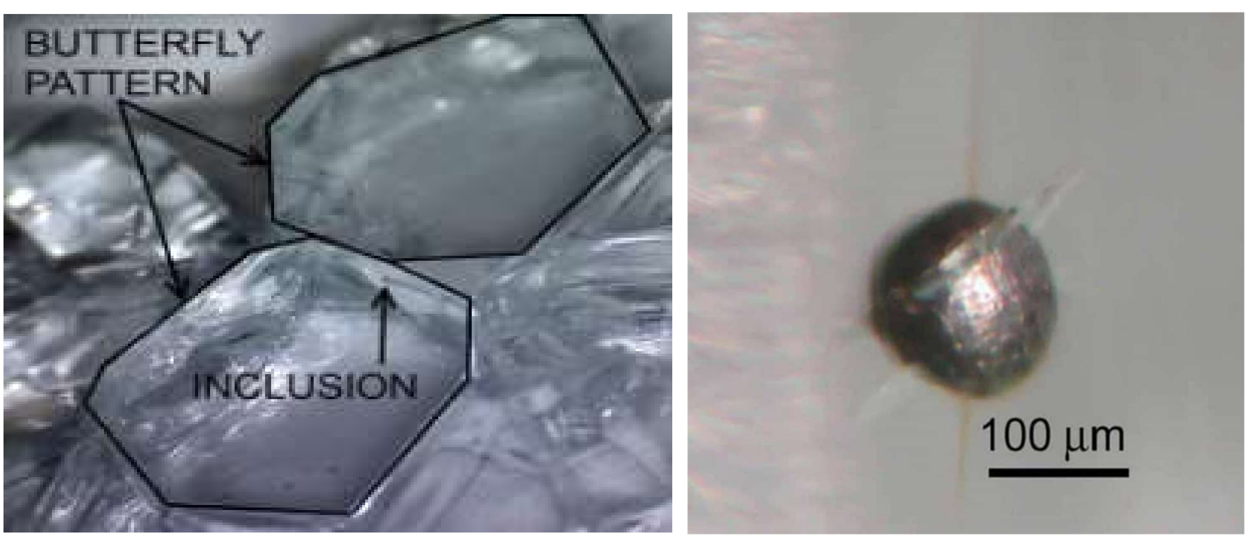


Figure 2-51: Nickel sulfide inclusion

So far, no known technology eliminates the possible formation of nickel sulfide stones and also no practical way to inspect its presence in float glass production. To minimize the risk of spontaneous breakages by Nickel sulfide (NiS) after glass construction, a destructive test called the heat soaking test must be performed.

Heat soaking test is a process in which tempered glass is subjected to a temperature of 290°c for several hours in a heat-soaking oven in the glass tempering company. During this time, the nickel Sulfide inclusions undergo a phase change (expand in volume). If the inclusions are near the central tension core of the glass, the volume change will generate sufficient stress to break the glass. It is estimated that up to 95% of nickel sulfide-contaminated panes of glass are usually destroyed by this process, reducing the chance of on-site spontaneous breakage.

Figure 2-52: Heat-soak testing oven

2.3.3 Sealants

Sealants are used to block water and air leakage through joint or surface openings in different materials. The sealant can be weak or strong, flexible or rigid, permanent, or temporary depending on the type of sealant. Most sealants are just fillers not adhesives but, if the sealant has an adhesive capability it is called adhesive (structural) sealant.

Silicone sealants are the most common choice for exposed or moving joints, although some curtain wall contractors do favor polyurethane sealants. Recognizing that all organic-based sealants will eventually fail, some contractors are using silicone sealants for all joints. Different silicone formulations make this approach more cost-effective. In some areas this requires a higher level of care but properly done provides a lower life cycle cost to the curtain wall system (CMHC, 2004).

2.3.3.1 Types of sealants

There are many different ways of categorizing sealants. Sealants can be classified based on their function, durability, cost, etc. Curtain wall sealants are classified into two depending on the function of the sealant application. These are:

A. Weather (joint) sealants
B. Structural (Adhesive) sealants

2.3.3.1.1 Weather (joint) sealants

Weather (joint) sealants are required to seal joints in framing elements, seal or provide backup seals to gaskets, and to use sealants in watershed and remedial functions. The performance of curtain walls for weatherproofing, building movement accommodation, insulation performance, and joint fill greatly rely on the type of weather sealant used. Silicone sealant is popular as a whether sealant in modern curtain wall construction.

2.3.3.1.2 Structural (Adhesive) sealants

Structural sealants are a special type of sealant that is used to adhere (with possible load transfer capability) two materials together. Adhesive sealants are largely used in curtain wall construction to bond Insulating glasses and glass with aluminum frames for structural sealant glazed curtain wall system. The sealants adhere the glass firmly to the aluminum as a means of structural support and load transfer. Structural silicone sealant is the common preference as a structural sealant as it balances the flexibility/stiffness requirements and provide the performance levels desired by the architect and engineer

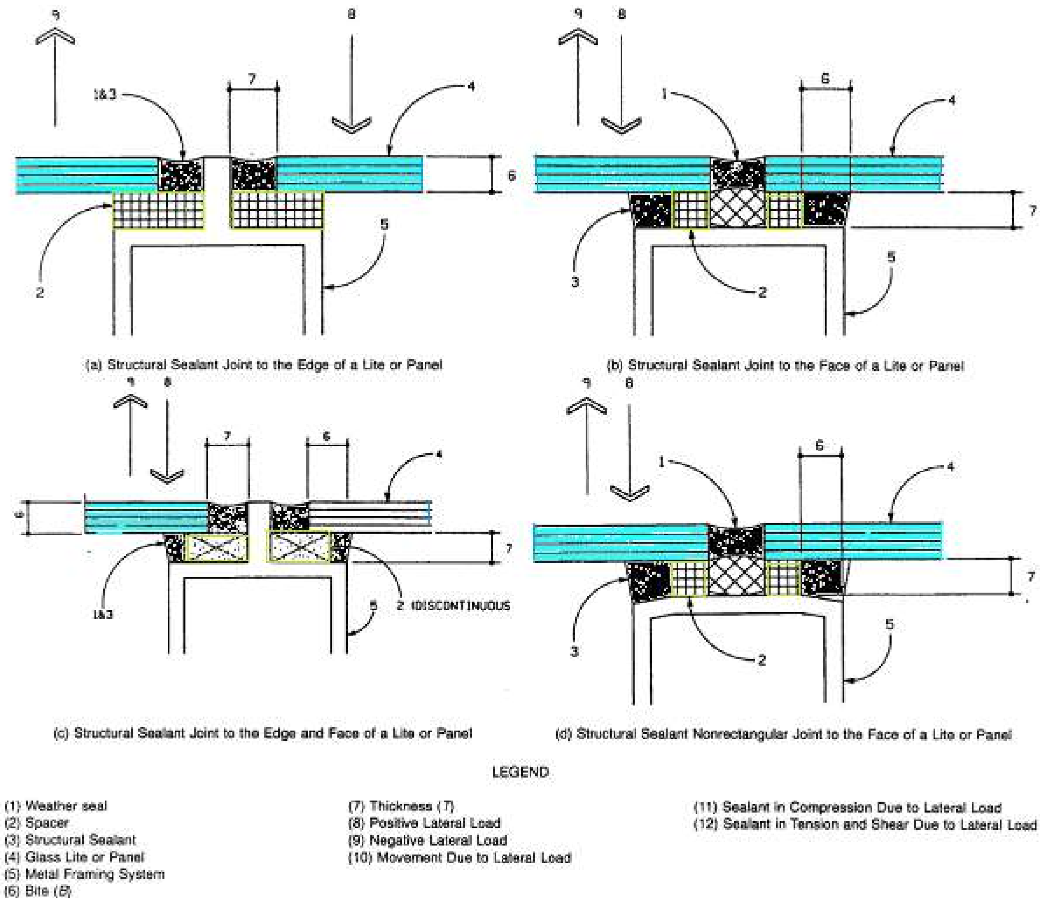


Figure 2-53: Typical weather and structural sealant joint configuration (ASTM C 1401-98)

2.3.4 Gaskets

Gaskets are rubber materials used to seal joint gaps and also to separate two different materials to avoid direct contact. Gaskets are products generally exhibiting a high degree of cure and elasticity and rely on their elasticity to maintain a seal. Available in a variety of shapes, hardness, density, and composition, gaskets are considered compression seals. They are placed in a joint and rely on interface pressure to create a seal (CMHC, 2004).

2.3.4.1 Types of gaskets

Gaskets are available in several different rubber materials. The most common materials used in curtain walls are neoprene, ethylene-propylene-diene-monomer (EPDM), and silicone gaskets. High-density polyurethane foam, usually produced with pressure-sensitive adhesive on one or two sides, is used as both gasket and spacer in structural silicone glazing. While usually called a glazing tape, based on cure, it is more properly considered a gasket (CMHC, 2004). Here are the two commonly used gaskets for curtain wall application:

2.3.4.1.1 EPDM gaskets

EPDM, which is an acronym for ethylene-propylene-diene monomer, is a type of synthetic rubber that is used in many applications from automotive products to HVAC parts. It is a very stable material that can resist heat, oxidation, and the aging effects of ultraviolet light. It also has good to very good resistance to steam, oxygenated solvents (acetone, methyl, ethyl ketone, and other ketones), animal and vegetable oils, alkalis, brake fluids, and compression set (https://www.henniggasket.com/).

EPDM is one of the most widely used synthetic rubbers in many static and dynamic applications. It is used extensively in outdoor applications where weather and water-resistance are required (www.elbex-us.com).

2.3.4.1.2 Silicone gaskets

Silicone rubber gaskets are high-performance mechanical seals with an extraordinary resistance to extreme temperatures. It also offers excellent resistance to ozone, oxygen, UV light, moisture, and fungus. Silicone gaskets have excellent vibration damping and maintains their dielectric strength with a low compression set and offer good fatigue resistance, flex resistance, and elongation (www.elbex-us.com).

Silicone gasket has poor tensile, tear, and abrasion resistance, and is not recommended for use in dynamic applications. Although high strength silicones have been developed, tear and tensile strengths remain relatively low. Its application as a curtain wall gasket is where silicone sealant is used to develop a good bond between the sealant and gasket for interior application (www.elbex-us.com).

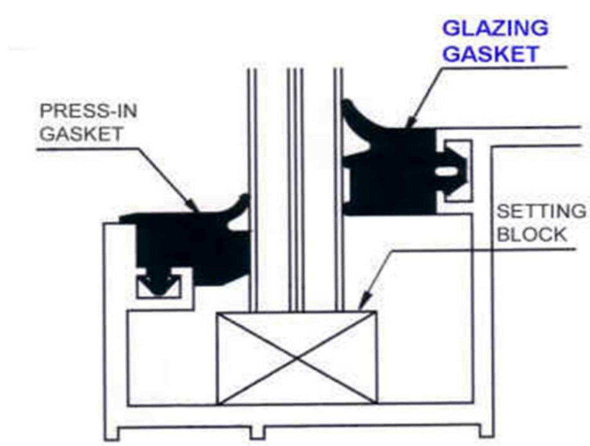


Figure 2-54: Gasket applied on curtain wall

2.4 Performance requirements and tests of curtainwall

In earlier times building facades are just considered as a sealed skin or envelope whose only function is to separate the variable and uncontrollable exterior environment from the more controllable interior environment as a barrier. However, the usage of façade only as an envelope does not apply to metal-framed glass curtain walls nor is it consistent with the growing trend toward green buildings.

In the Green building design concept, the building façade is considered more as a filter than a barrier between the external and internal environments. Glass and metal curtain wall systems should be considered a selective filter as they provide a barrier to some effects and allow passage of others depending on their design.

The curtain wall needs to be properly designed so that it can accommodate some of the structural and performance requirements. The following are some of the performance requirements of a curtain wall that needs proper design consideration.

1. structural integrity
2. control of water penetration
3. control of air leakage/airflow
4. control of sound transmission
5. control of heat flow and light transmittance
6. control of fire

2.4.1 Structural integrity

Curtain walls need to be designed to withstand its self-weight and any other applied loads on it without endangering life safety. Curtain wall structural stability is crucial as the other performance requirements are greatly dependent on it. It is a non-load bearing building structures that do not share any loads from the main building structure but rather transfers the applied loads on it to the structure.

The structural design of the curtain wall follows similar principles as any other wall design. However, the nature of the materials used for the structural design makes its design a bit complex. For instance, the brittle nature of glass and the elastic property of structural sealant materials makes it quite challenging to use them as a load-bearing element. Consequently, in curtain wall structural design the requirements of stiffness rather than strength usually govern. The need to accommodate movement and the need to limit flexibility is also the key concept for the structural design of the curtain wall.

Curtain walls are always designed for self-weight and wind loads. In addition to that, they are also designed for seismic load, impact load, temperature load, and any other loads which are directly applied to it. To accommodate the possible movements of the curtain wall due to temperature, slab deflection, column shortening, building sway, lateral drift, etc., there should be a designed joint or a gap.

While checking the structural integrity of the curtain wall, all components that withstand any kind of load or stress must be calculated. The glass, glazing system, Aluminum frames, connectors, and anchors must be checked for structural stability using the design load.

The structural stability test of a curtain wall must be done with a full-scale specimen based on the relevant standards. The most internationally accepted test standard to test the curtain wall for structural stability is ASTM *E-330 – [Test for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform STATIC Air Pressure Difference].* The specimen is checked for both serviceability and ultimate limit state. And for the inter-story drift testing *AAMA 501.4 – [Recommended static testing method for evaluating curtain wall and storefront systems subjected to seismic and wind-induced Inter-story drift.*

2.4.2 Control of water penetration

Water penetration is one of the most persistent performance problems faced by all types of walls. This problem worsens when the wall utilizes different materials with different properties and is assembled to act as a single wall. Due to the existence of more joints at the connections, metal-framed glass curtain walls have the potential to be greatly affected by water and air leakage.

The aluminum profiles of curtain walls have cavities that can accumulate water which in turn will damage sealants. It will also promote premature failure of insulating glass units and the curtain wall as a whole. The leakage of water through the curtain wall must be controlled before it enters the building interior and cause damages.

For water to leak through any openings of the wall, the following three aspects must be fulfilled. Eliminating one of these conditions, the water leakage will not occur.

i. Water
ii. Hole
iii. Differential pressure (or capillary action)

The water leakage control mechanisms which are being implemented on curtain wall construction are based on controlling either of these conditions. Three major water leakage control mechanisms are being practiced internationally. These are:

i. Exterior face seal
ii. Internal drainage
iii. Pressure equalization

2.4.2.1 Exterior face seal

Exterior face seal also known as face barrier system operates under the theory that the outermost face of the curtain wall system will be watertight, and thus water collection and drainage provisions are not necessary. In this system, blocking the water from getting inside the system by sealing all the holes (gaps) is the focus. However, sealing all the holes is very much difficult to achieve based on previous practices of curtain wall construction. This system is usually applied for a structural silicone sealant glazed curtain wall system as the weather sealant is applied around the perimeter of the glass on the outer face of the façade by incorporating the internal drainage system.

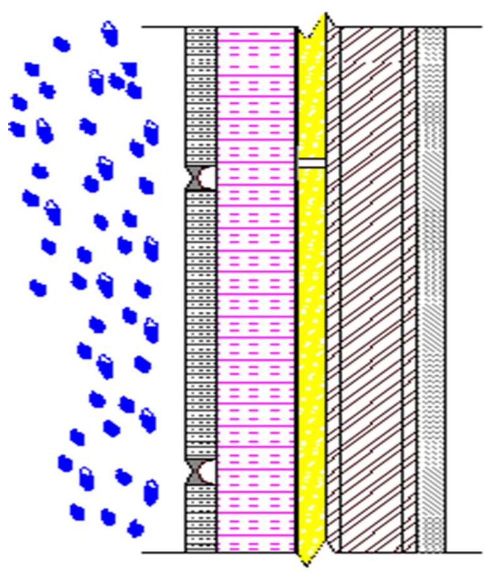


Figure 2-55: Exterior face seal method

2.4.2.2 Internal drainage

The internal drainage system is used in addition to the exterior face seal method to guide the water entered the system by providing a drainage path so that the water drains out instead of leaking inside the building. This system is especially vital for the visible frame curtain wall system as the gap between the glass and pressure plate is filled with gaskets (dry glazing) instead of silicone sealants (wet glazing). Since the glass is not perfectly flat and the gaskets also have variations, it is anticipated that water will enter around the glass as well as at exterior metal joints.

The internal drainage system should collect the water within the frame first, then diverts (guide) it to strategically located drainage points, and finally weeps the water back to the building exterior through weep holes.

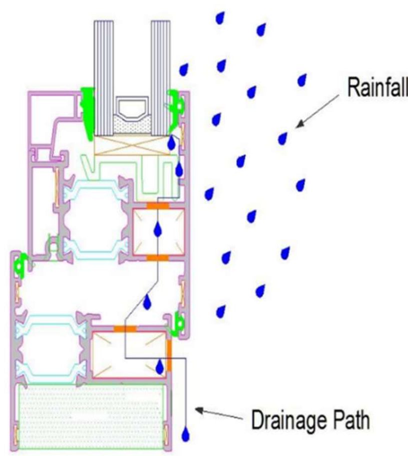


Figure 2-56: Internal drainage method

2.4.2.3 Pressure equalization

This system is based on a simple physical principle that under equalized pressure conditions, water is heavier than air and therefore falls under gravity instead of leaking. In this system, the main concept, therefore, relies on creating a chamber that will have equal pressure difference with the outside environment.

The design intent here is to provide a reasonably watertight exterior seal system coupled with adequate venting and drainage paths from the cavities behind. This technique is nowadays being implemented internationally by properly designing the aluminum profiles to incorporate a pressure equalization chamber in the section.

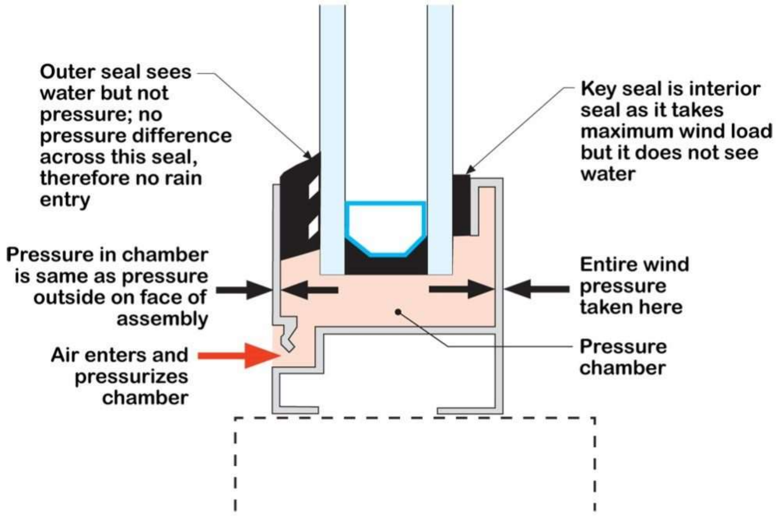


Figure 2-57: Pressure equalization method

The testing methods of curtain walls for water leakage in laboratories are standardized by different countries. The highly acceptable methods are ASTM E331 – [Test for Water Penetration of Exterior Windows, Curtain Walls and Doors by Uniform STATIC Air Pressure Difference] and AAMA 501.1 – [Standard Test Method for Water Penetration of windows, curtain walls and doors using DYNAMIC Pressure].

2.4.3 Control of air leakage

The curtain wall air leakage is concentrated at joinery, seals, and gasket locations. Controlling the air leakage is so crucial to improving the curtain walls' performances such as energy efficiency, moisture control, noise transfer control, smoke propagation during fire, indoor air quality, and curtain wall durability.

The air leakage control mechanisms are similar to that of water leakage control mechanisms. However, the standard used to test the curtain wall for air leakage on laboratories in ASTM E-283 – [Test for Rate of Air Leakage through Exterior Windows, Curtain Walls, and Doors].

2.4.4 Control of sound transmission

The goal of controlling sound transmission is to provide a curtain wall with an acceptable level of noise reduction. Buildings around airports and major highways might require sound transmission control through the curtain wall. The decibel (dB) is used to measure the sound level which uses a Logarithmic unit.

The steps followed for control of noise reduction are as follows:

i. assessment of environmental noise on the actual site
ii. determination of the minimum acceptable Transmission Loss (TL) or Sound Transmission Class (STC)
iii. selection of glazing and spandrel type

The sound control of the curtain wall could be enhanced by considering the following features of glazing design that impact an STC rating in the vision area such as:

i. glazing air gap thickness and spacer type
ii. glass thickness
iii. interlayer damping
iv. usage of insulation wools in spandrel panels etc…

2.4.5 Control of heat flow and light transmittance

To device a method on how to control the heat flow and light transmittance between the curtain wall, one must understand the source of this heat and light, the sun. Sunlight has *short-wave energy*, which comes directly from the sun, and *long-wave energy*, which doesn't come directly from the sun but re-radiated from other surfaces.

The sun short-wave energy encompasses three distinct spectrums based on their wavelength (nm).

i. **Ultraviolet (UV) light**: includes wavelength from 280-380nm (3% of solar spectrum)
ii. **Visible light**: from about 380 -780nm (44% of solar spectrum)
iii. **Infrared light (heat energy)**: from 780 – 4,000nm (53% of solar spectrum)

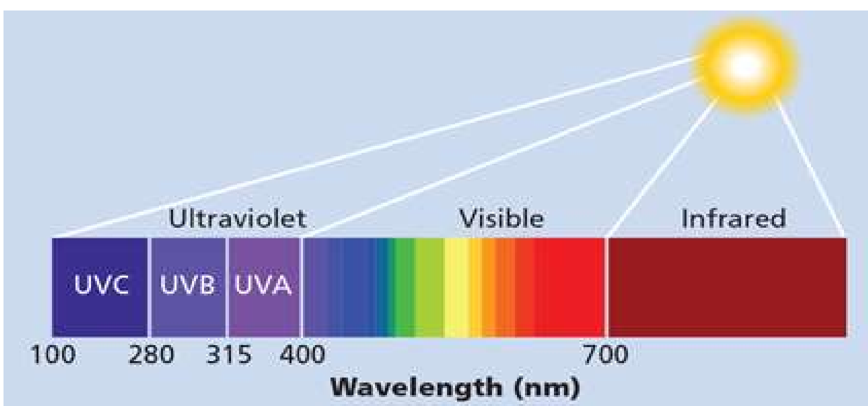


Figure 2-58: Solar spectrum

Curtain wall glasses will either reflect, Absorb, or transmit the solar energy coming from the different spectrums (UV, Visible light, and Infrared). Depending on the glass treatment and color, the rate and amount of energy reflected, absorbed, or transmitted will be different. Dark glasses generally absorb the most solar energy while Lighter tinted glasses transmit most of it.

Solar control Low-E glasses are designed to transmit high amounts of visible light and reflect Infrared light. On the contrary, Passive solar Low-E glasses are designed to transmit a high level of both infrared and visible lights. Reflective coated glasses generally reflect most of the visible light.

There are common terms used to describe the glass performance in terms of heat flow and light transmittance. Some of these are:

2.4.5.1 Visible Light Transmittance (VLT)

VLT is a percentage of the visible light portion of the solar energy spectrum coming through the glass. It measures glass's ability to transmit visible light which is crucial to allow daylighting in the building. It is expressed as a figure between 0% (no light) to 100% (all light). The higher VLT percentage means more daylight coming through the glass and no need for artificial lighting in the room during day time.

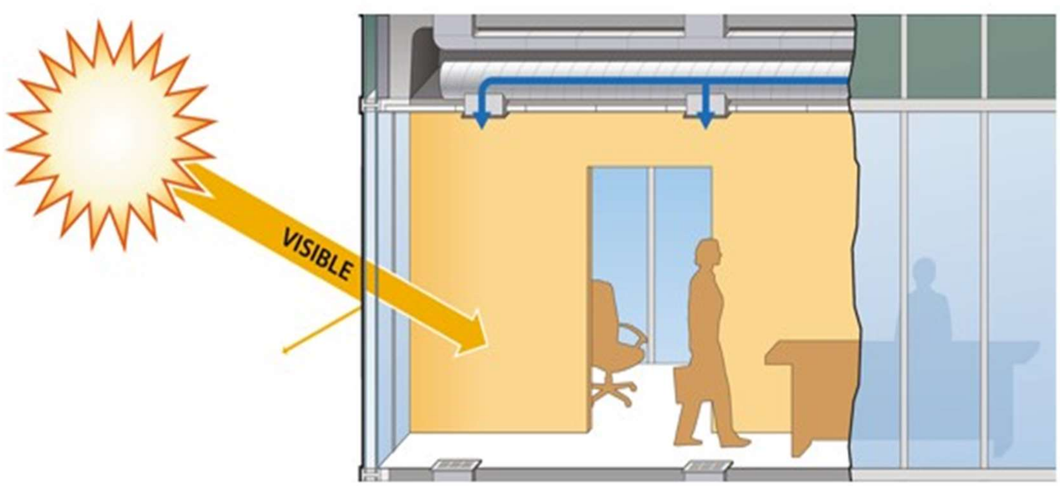


Figure 2-59: Visible light transmittance

2.4.5.2 Visible Light Reflectance (VLR)

VLR is a percentage of the visible light portion of the solar energy spectrum reflected by the glass. It is expressed as a figure between 0% (no light) to 100% (all light). A high level of visible light reflectance value means that most of the daylight is not passing through the window. If the sunlight hits the glass at a sharper angle, the visible light reflectance could be as high as 50% even though the glass used is clear.

Figure 2-60: Visible light reflectance

2.4.5.3 Solar Heat Gain Coefficient (SHGC)

SHGC is the fraction of incident solar radiation (Infrared) admitted through a window, both directly transmitted and also absorbed then subsequently released Inward. It is valued as a number between 0 and 1 and is always expressed in decimal. Zero represents an impenetrable wall against solar heat and one represents direct exposure to the sun's heat. The lower window's SHGC means less solar heat transmitted.

Shading Coefficient (SC) was used to express the solar heat gained by the glass in earlier times. It is the ratio of solar gain (due to direct sunlight) passing through a glass unit to the solar energy which passes through 3mm Clear Float Glass (0.87). To change values in the Shading coefficient (SC) to solar heat gain coefficient (SHGC) by multiplying it by 0.87 [SHGC =0.87*SC].

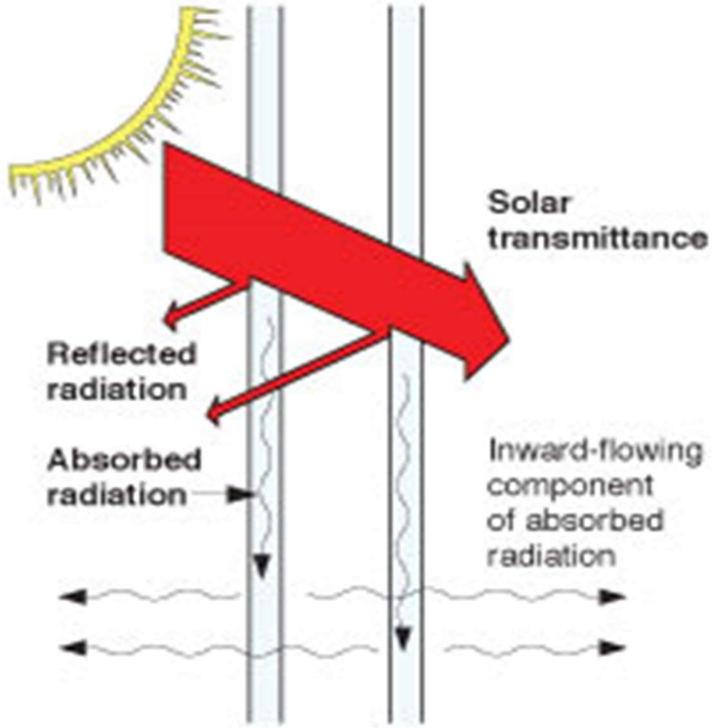


Figure 2-61: Visible light reflectance

2.4.5.4 Light to Solar Gain (LSG) Ratio

The LSG ratio measures the glass's ability to transmit Light and block heat in the form of infrared energy. This ratio can be calculated by dividing the Visible Light Transmittance (VLT) value by the Solar Heat Gain Coefficient (SHGC). The higher the LSG means, the brighter the room is without adding excessive amounts of heat.

$$LSG = VLT \div SHGC$$

2.4.5.5 Thermal insulation value (U-value)

Thermal insulation (U-Value) is a measure of the heat gain or loss through the exterior wall due to the difference between indoor and outdoor air temperatures. This is a decisive term while choosing the type of glass and curtain wall that can minimize the energy consumption of a building to heat or cool the interior room.

The unit of U-value in the metric system in watts(W) per one square meter (m^2) per kelvin(K) (W/(m^2.K). Double (multiple) glazing has a lower U-value than single glazing. Low-E coated glasses and body tinted glasses also exhibit lower U-values. Some glass samples show winter U-value and Summer U-value separately.

Winter U-value is a winter nighttime U-value measures the environmental conditions of a cold outside temperature and no sunlight. And A lower summer U-Value means the glass is better at blocking re-radiated heat, increasing the efficiency of the air conditioner.

It is the reciprocal of the U-value is R-value which is a measure of the resistance of the glazing to heat flow (R-value = 1 / U-value).

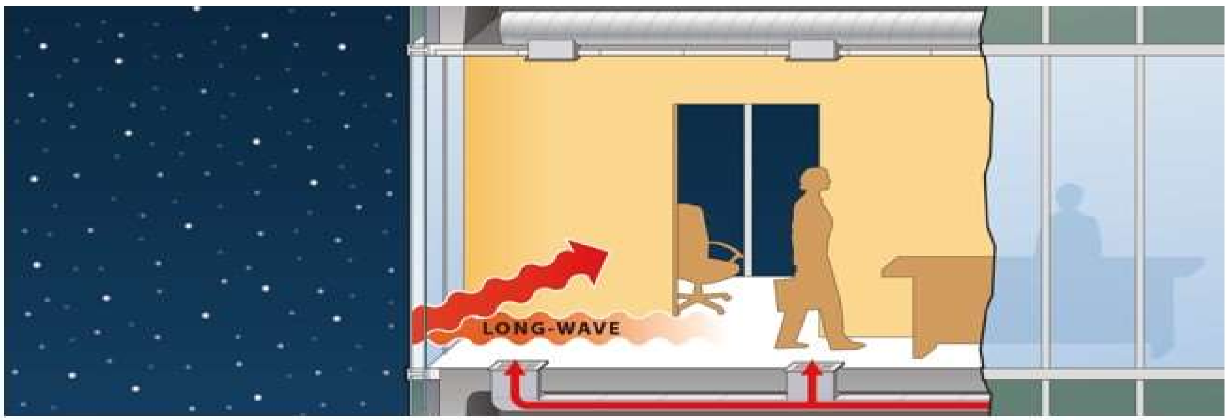


Figure 2-62: Winter U-value

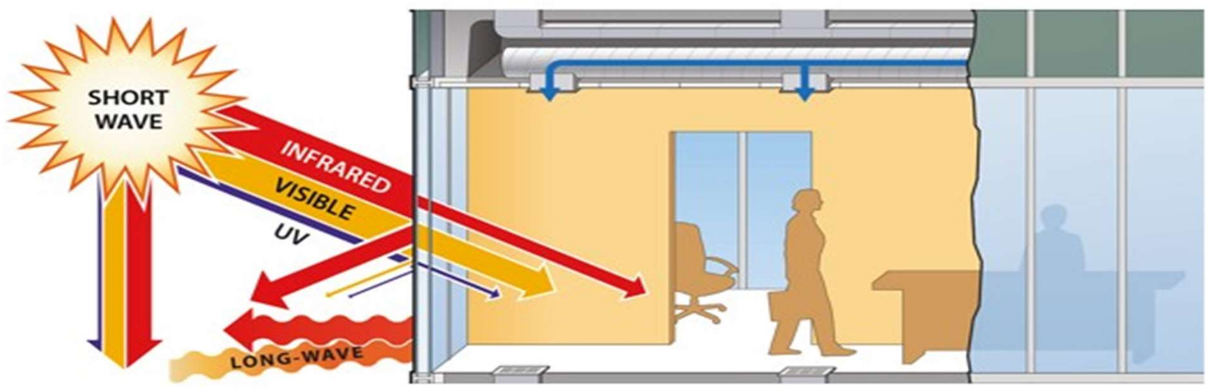


Figure 2-63: Summer U-value

2.4.6 Control of Fire

Curtain walls are required to be of non-combustible construction. Essentially all of the basic materials in a typical curtain wall assembly are non-combustible. But curtain wall design must consider how to control the spread of fire and most importantly the resulting smoke through the curtain wall. Some studies show that three fourth (3/4) of all fire deaths are caused by smoke inhalation.

Fire spreads through curtain wall to the next floors or rooms in the following manners:

2.4.6.1 Internal spread (Chimney effect)

The Chimney effect is when fire and smoke migrate from floor to floor, between the gap of slab and curtain wall. Proper fire engineering judgment and design on how to seal the gap to stop fire and smoke is required.

Fire insulation wools are used along the perimeter of the gap between the curtain wall and slab. For the smoke control, there is a fireproof sealant type used for controlling smoke passage from one floor to another.

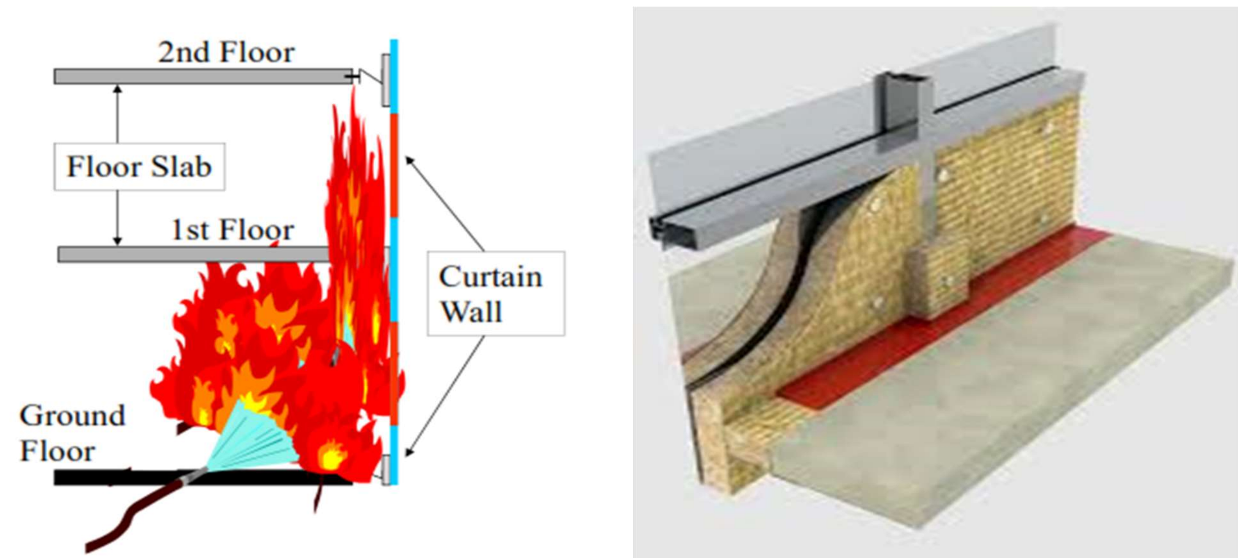


Figure 2-64: Internal fire spread (on the left-hand side) and Rockwool application (on the right-hand side)

2.4.6.2 External spread (Leapfrog)

During a fire, the vision glass part of the curtain wall will break within the first few minutes of a significant fire and lead fire to extend to the next floor on the exterior of the wall. The fire engineering must be done or appropriate standards must be followed while designing curtain wall spandrel panels.

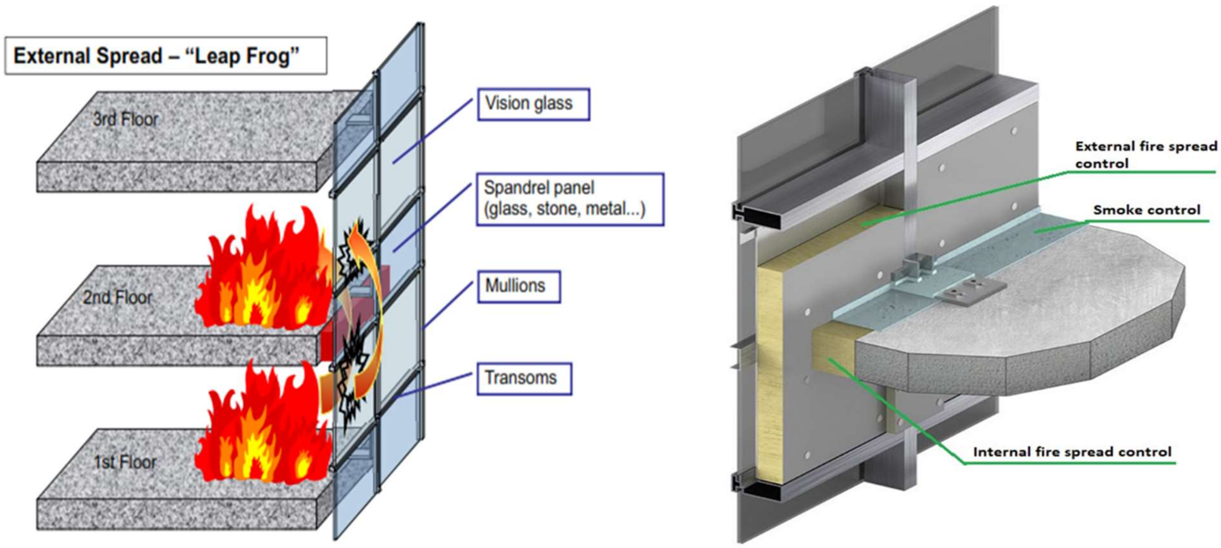


Figure 2-65: External fire spread (on the left-hand side) and Rockwool application (on the right-hand side)

3 LITERATURE REVIEW

3.1 General Introduction

The building enclosure (façade) in modern building construction is one of the key representations of the designer's demand for unique buildings (Ýlhan & Aygün, 2006). It is this desire that pushes designers to go for complex building forms which in turn creates complex facades.

Merriam dictionary defines the word façade as "the *front of a building also: any face of a building given special architectural treatment*". Accordingly, the word "façade" has been used by many to represent the exterior element of a building that separate the building interior against the outside environment.

Building Façades have evolved through time from being a solid load-bearing wall with small window openings to the state-of-the-art of fully glazed facades with no or minimal visible frame support (Zamora & Calderon, 2007). Of all building façade types, metal-glass façade (usually termed as Curtainwall) predominantly has been influenced due to this modern building Architectural evolution (Ýlhan & Aygün, 2006).

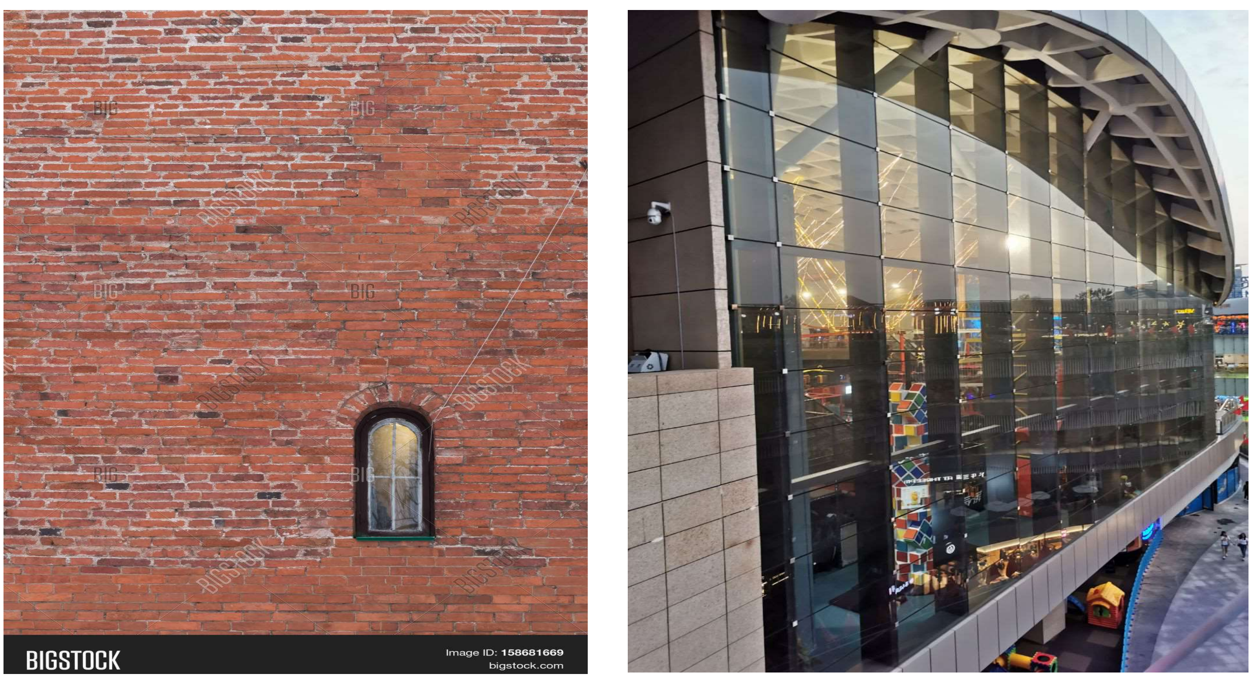


Figure 3-1: Traditional brick wall with a small window opening (left-hand side) and a modern fully glazed Wall (right-hand side)

Traditionally, building facades were part of the building's load-bearing structures built from stone, brick, concrete, etc. with a provision of small glass windows for ventilation and natural light (Kazmierczak, 2010). However, nowadays building walls are becoming non-load bearing as the building structures are being built using reinforced concrete and steel so that the façade will only bear self-weight and loads directly applied on it (Pitroda et al., 2016).

The revolution of industrialization and continuous technical advancements on the Aluminum extrusion process and glass manufacturing methods played a vital role in the emergence of curtain wall as a symbol of modern building façade Architecture (Afghani Khoraskani R, 2015).

Curtain wall advancement overtime does not only focus on the aesthetic aspect but also focuses on performance requirements. Although, the need for water and air leakage control and structural stability of curtain walls are the basic performance requirements and the basis of curtain wall design (Quirouette & Arch, 2013), conservation of energy is now becoming the core of modern curtain wall design advancement (Ýlhan & Aygün, 2006).

Developments in the glass manufacturing industries in terms of thermal and structural performance play a key role in buildings energy-saving curtain walls. These types of curtain walls will have a significant impact on the running cost reduction for high-rise buildings with a fully glazed façade as they consume a significant portion of building energy (Ming Hu, 2013).

The manufacturing breakthrough for glasses used on building façades is related to the invention of float or distortion-free glass production process which greatly enhances the transparency and surface quality of glass (Yussof, 2015). All types of glasses used for building façade like thermally toughened, laminated, IGU, etc. are produced by using a float glass.

Thermally toughened and laminated glass inventions greatly improve the structural performance of glass while IGU (Insulating Glass Unit) enhances the thermal, acoustic, and Energy conservation performance. To further enhance the thermal performance of curtain walls, Low emissivity (Low-E) coatings and different gases inside the air gap started to be used for IGU glasses.

On the other hand, it is now becoming an international norm to use extruded Aluminum profiles as a structural support for fully framed glass curtain walls (Lee et al., 2017). The current advancements in the lightweight, metal-framed curtain wall systems might not be achieved if it was not for the versatility of extruded Aluminum profiles to the required shape and structural requirement.

The use of sealants (most commonly Silicone sealants) as a structural and weather sealant avoiding a mechanical fixation between glass and Aluminum frame also plays a vital role in modern curtain wall advancement (Afghani Khoraskani R, 2015). Attaching the glass with the frame using a high-performance structural sealant allows Architects to design large glass dominated curtain walls.

On the international market, the two dominant curtain wall types based on the method of construction are the Stick-built curtain wall system and the Unitized curtain wall system. Although, stick-built system is the oldest and most common choice of building façade in the past, nowadays the use of a unitized curtain wall system is dominating especially for high-rise building facades.

The state of the art for the high-rise buildings design allows many Architects to design a very complex shape of buildings which also leads to complex facades. As the primary choice of high-rise building façade, the unitized curtain walls are also becoming complex.

Although the unitized curtain wall is preferable for high-rise buildings due to its superior quality over stick-system, designing and constructing complex-shaped unit panels is not an easy task. That's why a full-scale performance test is recommended to cross-check with the design.

3.2 High-rise building façades

(Ming Hu, 2013) used the term super high-rise buildings for buildings having a height of more than 100m or 30floors. For the sake of this paper, the same arrangement will be used but for high-rise buildings rather than super high-rise buildings.

Nowadays, the use of a curtain wall as a building façade in modern cities is quite common (Quirouette & Arch, 2013). An aluminum-framed glass curtain wall is the common choice of high-rise buildings façade due to its Architectural, structural, and performance advantages (Yu Wang et al., 2014).

Figure 3-2: High-rise buildings curtain wall facades

While designing high-rise buildings different factors are going to be considered such as structural stability, vertical access (transportation), Mechanical and electrical aspects, aesthetical appearance, functionality, comfort, and building envelop. The envelope (façade) design must be well integrated with all these items (Ming Hu, 2013).

Different studies put the cost of a high-rise and supper tall buildings façade (curtain walls) between 15-25% of the total project cost (Stephens, 2014). This is one of the reasons for the need for proper designing, full-height testing, and construction of curtain walls.

The practice of using a glazed curtain wall for high-rise buildings located in the major international business districts such as Hong Kong, Dubai, and Shanghai is a good example of curtain walls growing demand as a building façade (Lee et al., 2017).

In Ethiopia, the use of curtain walls for building façade is growing at a faster rate in the past two decades although, most of the curtain wall projects are concentrated on commercial buildings. The curtain wall types used are almost all stick-built curtain wall system.

Due to the political and economic advancement of the capital city, Addis Ababa, the country's financial institutes start building high-rise buildings at the newly established financial district. The building façade types used by almost all of the high-rise buildings constructed in the financial district are Aluminum framed glass curtain walls.

Figure 3-3: The financial district of Addis Ababa

The biggest issues with high-rise building curtain wall type selection are the weight of the façade, the ability to accommodate and withstand wind and lateral load-induced movements, the high-level performance of water and air leakage control, and cost. These issues will become of higher interest when the façade becomes complex.

The unitized Curtainwall system is becoming more popular and common choice of façade for high rise buildings worldwide. Aluminum framed and glass infill unitized curtain walls secret for such an international acceptance relies on their Lightweight, maximized, and controlled quality, wind and thermal-induced movement tolerance, ease of installation, and relative cost reduction as the glazing area increase for high-rise buildings (Ilter et al., 2015).

3.3 Stick-built vs unitized curtain wall systems

Stick-built system and unitized system curtain walls are the two major Aluminum framed glass curtain wall types based on classification by method of installation (Ýlhan & Aygün, 2006). The stick-built curtain wall system is the oldest curtain wall type developed by the industry (Quirouette & Arch, 2013). Through the technological advancements in the manufacturing industry, there are now many types of curtain walls on the market: Energy-efficient unitized curtain wall being the state of the art for high-rise building façade.

The stick-built curtain wall system is categorized as the first generation of the curtain wall. The second generation of curtain walling started with the invention of a unitized curtain wall to ease the on-site construction process and to minimize installation time. The third-generation curtain walls refer to curtain walls, the basic one being a unitized curtain wall, characterized by energy efficiency (Yuanda China Holdings Limited. Global Offering., 2011).

Stick-built curtain wall system is still the primer choice for most of the high- and low-rise buildings of Ethiopia although, nowadays some of the leading high-rise buildings are adopting the unitized curtain wall system as their façade system. Even though there are a lot of reasons for getting stuck on the traditional practices, the knowledge limitation seen on the building construction stakeholders about the different types of Aluminum framed curtain walls is the critical factor.

However, International reports show that the unitized curtain wall system not only overtake the predominance of stick-built system but also it almost doubled the world-wide spending of money on stick-system in 2012GC as it is adaptable for technological advancements and have consistent quality (Yuanda China Holdings Limited. Global Offering., 2011).

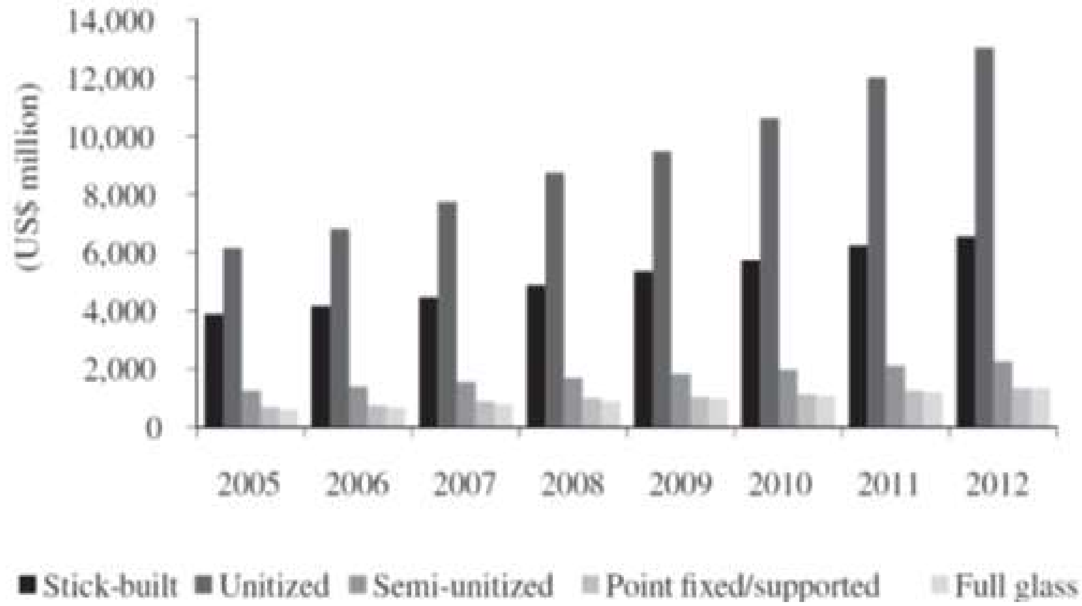


Figure 3-4: Market segmentation of the global curtain wall industry by product type (Synovate Report)

Table 3-1 shows the comparison of stick-built and unitized curtain wall systems:

Table 3-1: stick-built vs. unitized curtain wall systems comparison

No.	Description	Stick-built curtain wall	Unitized curtain wall
1	Availability of Aluminum profiles on the market	Standard profiles	Custom made profiles
2	Design and preparation lead time requirement	Less	High
3	Construction method	On-site assembly and installation	Workshop assembly and on-site panel installation
4	Production time on workshop	Less	High
5	Installation time on site	High	Less (only 33% of stick-built system)
6	Design complexity	Less	High
7	Complex shape adaptability	Excellent	Good
8	Preference for high-rise building façade	Moderate	Excellent
9	Movement accommodation	Less	High
10	Precision requirement	Moderate	High
11	Cost	Good for small glazed area	Good for larger glazed area
12	Quality control	Moderate	Excellent

Most of the time unitized system curtain wall is advised for structural sealant glazed curtain wall systems to control the sealant application quality in the workshop (CMHC, 2004). When the two are used in combination (structural sealant glazing system on unitized curtain wall), the curtain wall will become the best choice for seismic susceptible areas as the glass reduce the risk of breakage due to collision with the Aluminum frame (Memari et al., 2012).

3.4 Complex Unitized curtain wall systems

3.4.1 Morphological complexity

Nowadays more and more high-rise buildings are adopting too complex shapes of building structures which also require complex enclosing facades with high-performance efficiency (Clift & Austin, 1989). The growing Architectural requirements of building enclosures as a result of the fast-technological advancements contribute to the revolutions of complex geometries of façade (Vollers, 2004).

Unitized curtain wall is an excellent choice for straight and orthogonal shaped facades. However, for non-orthogonal shaped facades, design strategies are required so that the façades can be built using unit panels (Ligthart, 2011a).

The complexity of a curtain wall comes from the complex form of the building's Superstructure. Usually, complex curtain walls are termed for façades with forms (shapes) like twisted, double curved, or inclined singularly curved shape which meets the floors with different inclinations (Vollers, 2004). Twisted facades follow twisted building structures in most cases being diagrid frames (Akkoyunlu, 2018).

Figure 3-5: Highrise towers with twisted façade around the world

(Ligthart, 2011b) presents the different primitive shapes and transformation commands in a manner to show different modern high-rise building shapes and the corresponding facades. The façade shapes can be either a primitive shape alone or using a combination with the transformation commands.

The façade surface with a different combination of the primitive shapes and the transformation commands with the design and construction complexity using the current technologies is well described as shown in Figure 3-6 by (Ligthart, 2011b).

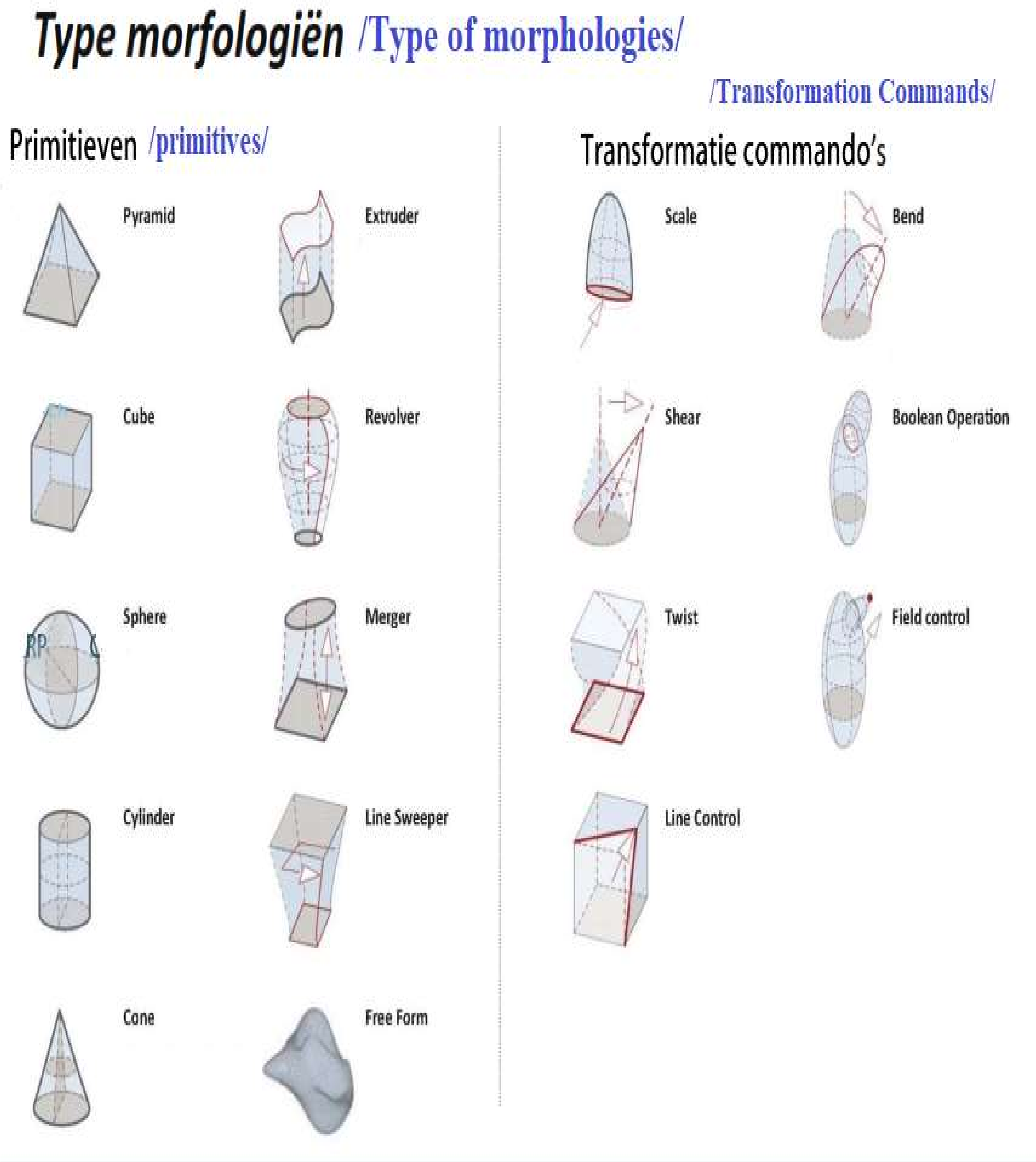
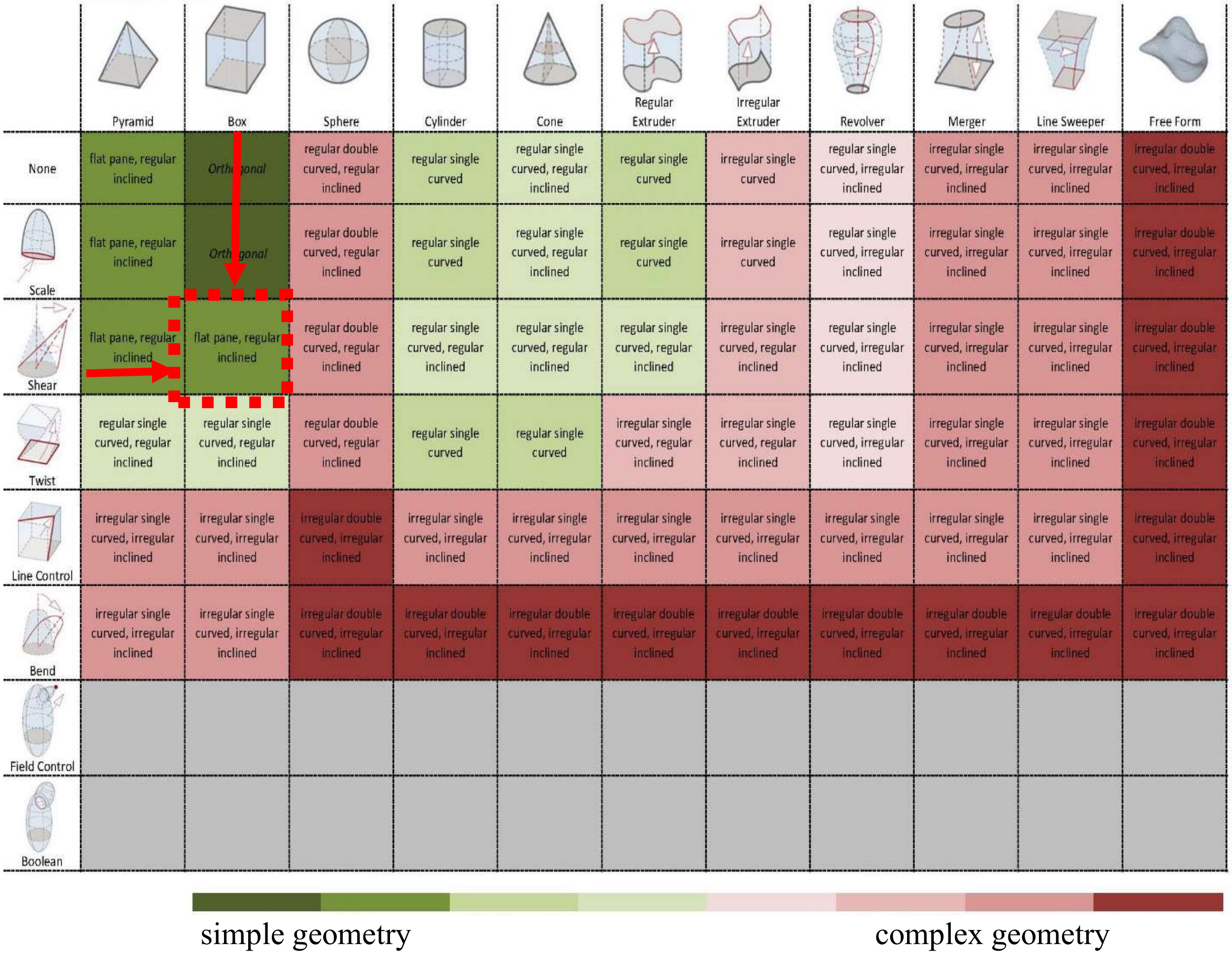


Figure 3-6: Types of morphologies (Ligthart, 2011b)



	Pyramid	Box	Sphere	Cylinder	Cone	Regular Extruder	Irregular Extruder	Revolver	Merger	Line Sweeper	Free Form
None	flat pane, regular inclined	Orthogonal	regular double curved, regular inclined	regular single curved	regular single curved, regular inclined	regular single curved	irregular single curved	regular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined
Scale	flat pane, regular inclined	Orthogonal	regular double curved, regular inclined	regular single curved	regular single curved, regular inclined	regular single curved	irregular single curved	regular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined
Shear	flat pane, regular inclined	flat pane, regular inclined	regular double curved, regular inclined	regular single curved, regular inclined	regular single curved, regular inclined	regular single curved, regular inclined	irregular single curved, regular inclined	regular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined
Twist	regular single curved, regular inclined	regular single curved, regular inclined	regular double curved, regular inclined	regular single curved	regular single curved	irregular single curved, regular inclined	irregular single curved, regular inclined	regular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined
Line Control	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined
Bend	irregular single curved, irregular inclined	irregular single curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined	irregular double curved, irregular inclined
Field Control											
Boolean											

Figure 3-7: facade surface morphology complexity clarification (Ligthart, 2011b)

It can be easily seen that the complexity level of facades from simple to complex is done based on the geometry. However, the level of complexity related to the construction difficulty and the existence of additional attached components on the unitized façade is not considered.

For instance, the sheared box type façade surface is categorized as a simple geometry façade morphology. The façade is described as a flat plane that has a regular inclination. The categorization only takes the primitive shape of the box with the transformation command shear. However, if two different angle shears appear on the same floor and the same panel the complexity of the façade becomes higher.

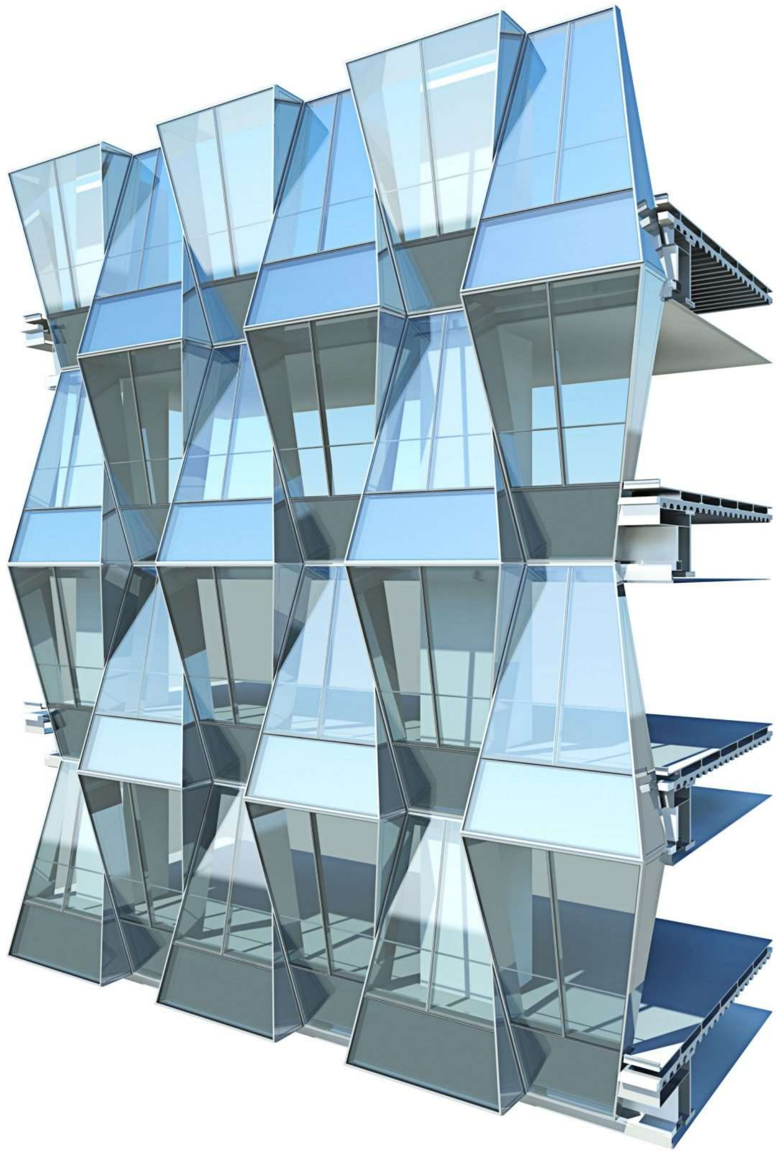


Figure 3-8: Double sheared complex unitized curtain wall

When the façade has both the inward and outward inclinations within a single panel, the vertical mullion members become a joined member of two mullion profiles, and the level of complexity increases. And when additional elements are added to the unitized curtain wall panels, it further complicates the façade design and construction.

The construction and design complexity of double sheared box façades needs to be investigated based on the additional parameters like the presence of joined mullions within the floor span, the degree of shear and the angle created at the junction, the decorative or other attached element, etc...

It is a common practice to use a continuous mullion for the full span of a floor or two for both stick-built and unitized curtain wall construction. Accordingly, when researches and studies of the curtain wall are done, the mullion members are considered as a full span and deflections of those mullions are checked.

However, when the mullion members span full floor height by joining two mullion profiles using a connector within the span, the structural integrity and the performance of the façade must be checked.

The effect of using a joined mullion profiles in a unitized curtain wall system needs to be investigated to fully understand the effect concerning the joint movement and the corresponding effect on the supported glass. In this paper, the numerical analysis and full height test displacement results of such joints are checked in addition to the other full floor height spanning continuous members.

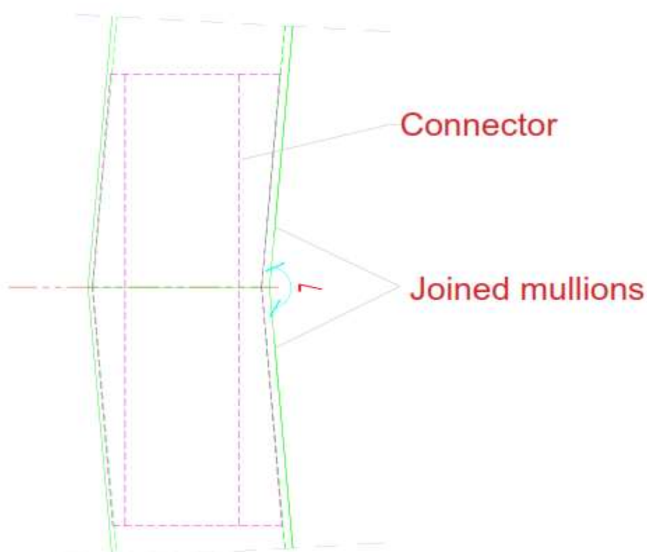


Figure 3-9: joined mullion using a connector

On the other hand, when the line that results in double angle shearing within the façade that spans multiple floors, not only the mullions but also the stack-joints will be joined Aluminium profiles.

It is the stack joint where the top and bottom panels are installed together and any relative movements caused by inter-story drifts and live load deflection will create a relative movement between the head and bottom stack-joints.

(Ali M. Memari et al., 2018) the study of unitized curtain wall system under dynamic inter-story test as per the AAMA 501.6 protocol recommends that it is vital to properly design the stack joints to avoid neighboring panels to sway together or slide in the same direction and avoid racking. This can be achieved easily on straight and planar unitized curtain wall panels which have no hindrance.

However, when the stack joint profiles within a single panel are joined together using connectors at an angle, then the possibility of the panel sliding above a certain level might be interrupted. Although the level of panel sliding interruption highly depends on the type (dynamic or static) and magnitude of the inter-story test, the connection angle of the stack-joints also affects it as sharp connection does not promote sliding movement but rather sway and possibly rack.

Understanding the effect of joined stack joints at an angle is vital especially when it exists on seismic susceptible areas. It also needs a well-established lab setting and testing for dynamic load to have a clear image of how the joined sharp connections affect the overall structural performance of the unitized curtain wall system.

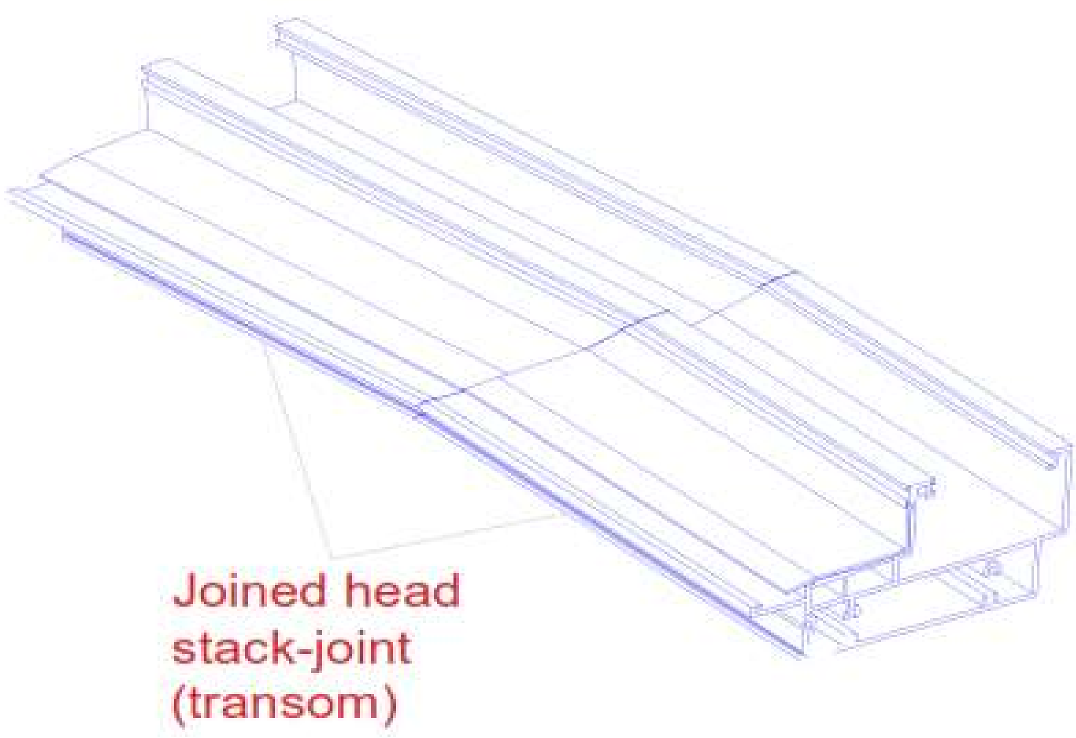


Figure 3-10: Joined head stack-joint (male transom)

3.4.2 Complex unitized curtain wall materials

The emergence of complex unitized curtain wall systems is directly related to the emerging technological advancements with the production possibilities (Vollers, 2004). Complex forms of curtain walls require complex /sophisticated/ design of the constituting materials.

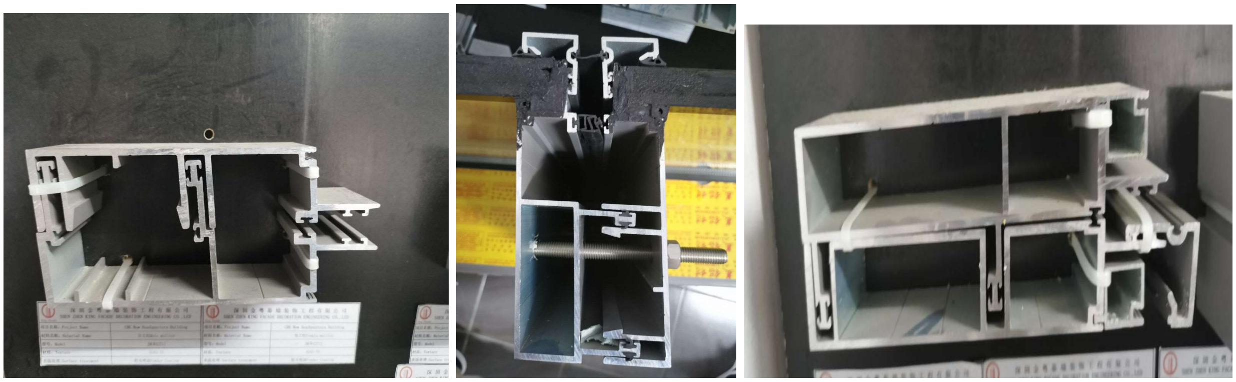
The two most affected materials due to the complexity of the unitized curtain wall are the Aluminium Profile and the glass. Curved or twisted profiles and transformed glasses are being required for the current state of the art facades we are seeing in the world (Vollers, 2004).

In modern curtain wall construction, the common structural supporting frame material is Aluminum (Lee et al., 2017). As the high-rise building's shape is becoming more and more complex, the façade enclosure must also synergize those complexities. Extruded Aluminum profile is the best choice of curtain wall support for complex facades as it is a versatile material (Kesawan & Mahendran, 2019).

The Aluminum profiles used for unitized curtain wall systems adopt usually project-specific custom-made profiles. This practice gives the designers total control for designing a safe and economical profile cross-section for any type and shape of building Façades (Lee et al., 2017). Depending on the required function from the extruded aluminum profiles, designers can integrate multiple features into the customized aluminum profile cross-section (Yongbing Wang, 2006).

Despite the standard shape of rectangular Aluminum profiles used for stick-built curtainwall system mullion and stack joints, the unitized system commonly adopts C and *E-shaped* male and female Aluminum profiles (Lee et al., 2017). Generally, the male and female mullions or the stack joints are not fixed to one another as they are designed to allow movements of the curtain wall due to the external loads like wind, seismic, and temperature (Kesawan & Mahendran, 2019).

The three most common cross-sectional types of the E-shaped Extruded Aluminum profiles are open type, boxed type, and double-boxed type profiles (Lee et al., 2017).



a) b) c)

Figure 3-11: E-shaped Aluminum profiles a) open type b) boxed type and C) double boxed type

One of the challenges for unitized curtain walls, especially complex ones, is the inefficiency it creates if the curtain wall modules have little repetition, varying size, and span(CMHC, 2004). Consequently, the Aluminium extrusion and the glass production process will become complex and costly.

The different morphologies of the building façade require different types of custom made Aluminium profiles. For complex facades such as twisted towers, twisting the Aluminium profile might also be the future possibility with technological advancements (Vollers, 2004).

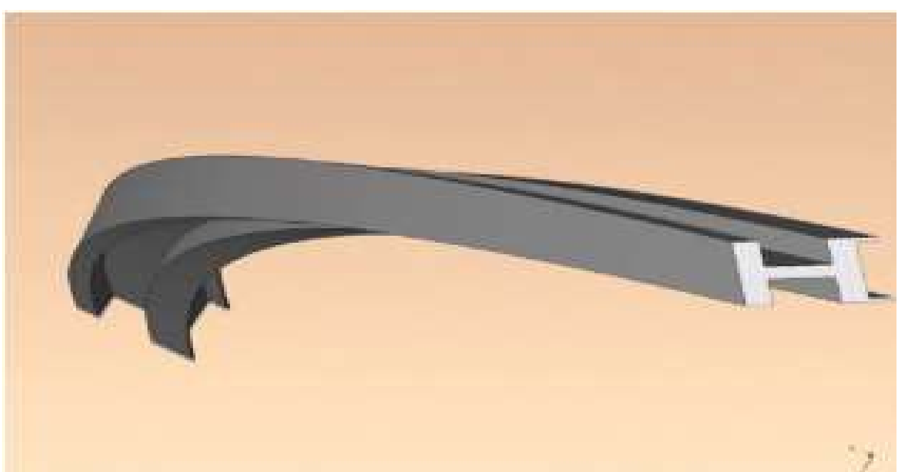


Figure 3-12: Twisted Aluminium profile for twisted curtain wall (Vollers, 2004)

However, simple to medium complex curtain walls (such as sheared box façades) adjusting the cross-sectional shape of the profiles to provide the required continuous support to the glass while assuring easy connection with the supporting structure might be enough.

The form of the glass infill for the complex facades follows the required shape of the building whenever possible. Singly curved and doubly curved façade's glass can be manufactured with the current state of the art technology.

Figure 3-13: Single curved IGU glass

Figure 3-14: doubly curved IGU glass

For simple forms like sheared box facades, on the other hand, making the glass parallelogram or other shapes while it is still a flat glass could be enough.

3.5 Design principles of unitized curtain walls

The structural design of the unitized curtain wall is done similarly to the stick-built system on the façade design industry. The design of the glass, structural sealants, connectors, and support of both unitized and stick-built curtain walls is absolutely the same. The major structural design difference usually happens on the frame analysis modeling.

In the common flat curtain walls, the mullion (vertical element) is the main structural element that withstand and transmit the self-weight and the applied loads to the building's main structure at floor level (Lee et al., 2017). The transoms (horizontal frame elements) which mostly span between two mullions carry the dead load of the infill material (mostly glass) in addition to restraining the lateral-torsional buckling of mullions due to wind and seismic loads on the curtain wall (Clift & Austin, 1989). However, no stiffness or restraints from the infill materials are considered in many structural design analysis of curtain walls (Lee et al., 2017).

The mullions and transoms of the stick-built and unitized curtain walls are designed as a simply supported beam (Wong wan sie, 2007). The curtain wall members are designed using the Euler-Bernoulli beam theory. Pin connection is applied where the curtain wall and the building structure meet and hinge between adjacent mullions (Lee et al., 2017). The frame releases also follow the same approach while modeling in Finite Element modeling software.

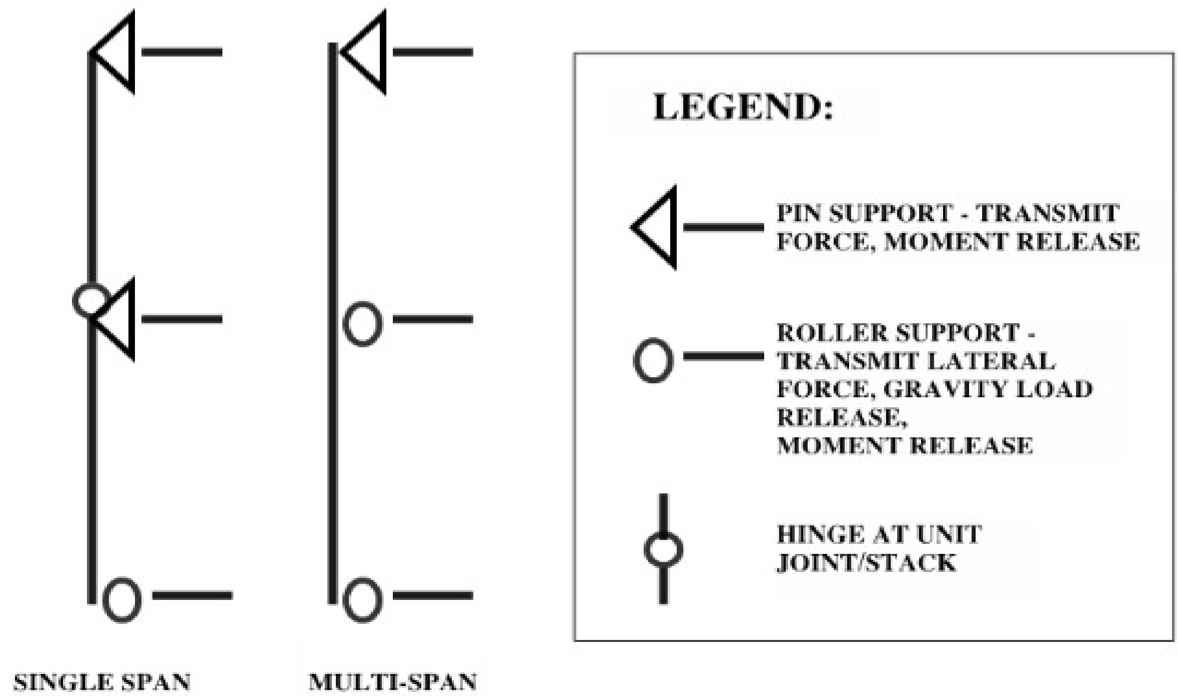


Figure 3-15: mullion spanning and support modeling method (Pond et al., 2003)

(Wong wan sie, 2007) suggests a minimum of 4 floors spanning mullions for the structural analysis and design of unitized curtain wall. Although this approach is adopted by many for stick-built and in some cases for unitized systems, it fails to incorporate the torsional and even deflection restraining factor of the transom and the effect of lateral in-plane loadings on the mullion design even if it is on the conservative side.

Whenever possible the full or a representative section of the Unitized curtain wall modeling is advantageous instead of just modeling the mullion and transom alone. Especially when the comparison between the Finite analysis and test results of a unitized curtain wall is required, the model needs to represent the test specimen as much as possible.

Although on the structural analysis modeling the male and female mullions of unitized curtain walls are combined to become a single member which has their combined section property, the structural design check of the members is done individually. These combined mullion sections are subjected to bending stresses due to the perpendicularly applied wind force on the curtain wall (Kesawan & Mahendran, 2019).

The pattern of the multi-story mullion deflection, shear, and bending moments are presented by (Lee et al., 2017). The broken line is the support location while the solid horizontal line is the stack-joint location.

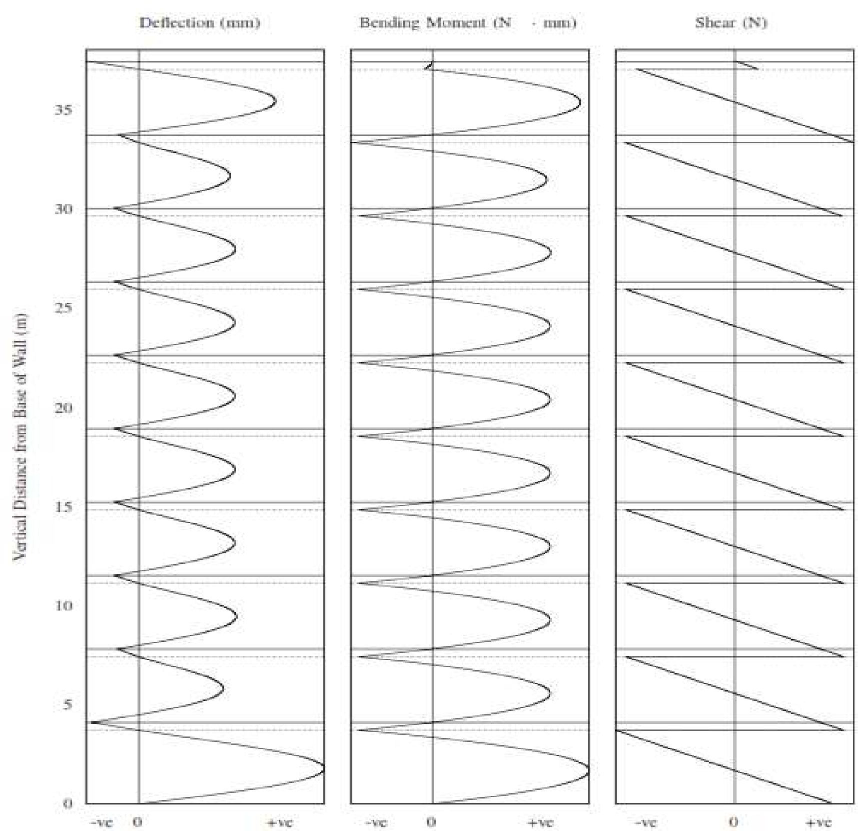


Figure 3-16: deflection, bending moment, and shear patterns of a unitized curtain wall (Lee et al., 2017)

Taking only the deflection pattern it can easily be seen that the out of plane deflection at the support locations are zero as the supports are either pin or roller with restricted translation in the y-direction. However, on the actual construction, these can be achieved if only there is no gap between the panel supporting hook and the p-clip (support bracket).

For the unitized curtain wall analysis, using the commonly used structural analysis software like SAP 2000 or other similar Finite element-based software can be used. The analysis results of both the serviceability and ultimate limit states can be used for further designing of the curtain wall components.

However, there is a major gap to properly design the seismic (inter-story) behavior of the unitized curtain wall on those analysis software tools. The difficulty to model the mullions and stack-joint as close as possible to the actual condition (male and female transom) is one of the key shortcomings of the current unitized curtain wall analysis and design practice in the industry.

Structural design of glass can be done either by using Finite Element software or by using other standards. The most common curtain wall glass design standard is *ASTM E-1300 – Standard practice for determining load resistance of glass in buildings*.

The structural silicone sealant bite width and thickness must also be designed properly as it is the critical structural bearing element to support the glass while it is an elastic material. There are many standards for calculating the structural sealant width and thickness and most of the time, the manufacturers will provide the design formulas by themselves.

One of the key advancements of the unitized curtain wall from the stick-built system is its capability to accommodate different movements induced by either temperature or lateral loads. To accomplish that there will be some gaps between the male and female mullions and also at the stack-joints (male and female transoms). These gaps must be designed to accommodate the expansion or contraction movements of the unitized panels due to changes in temperature, assembly and construction error tolerances, the supporting slab structure differential live-load deflections and column shortening, and seismic (inter-story drift) induced movements.

3.6 Full height tests of curtain wall

Curtain wall panels are assembled using different materials that have different characteristics. Such construction methods are susceptible to performance problems as the curtain wall is required to control water and air leakage while maintaining its structural Integrity.

To ensure that the proposed and designed curtain wall systems fulfill the required performance standards it is advised to do a full-scale performance testing. The size of the test specimens usually governed by the type of curtain wall, the size of the walling area, and the owner's requirements.

The standards for water and air leakage test, and also the structural performance test can be done with a single floor specimen as long as it includes the existing joints, cracks, or openings of the design. However, for the inter-story drift, it is required a minimum of two floors with the stack joint to fully simulate the movement of the unitized curtain wall.

For high-rise buildings with unitized curtain wall, it is advisable to select a multi-story test specimen to fully check the performance of the curtain wall system and the corresponding workmanships.

Many researchers are using single floor panels to check only some aspects of the performance test as the cost to do a multiple floor test for research purposes is high. Most of these researches are done to understand the dynamic inter-story drift behaviors of curtain walls.

Although, test specimens for research purposes must be done under a controlled environment, for such costly testing it is also a good start to incorporate research components for checking on the actual project-specific tests.

4 NUMERICAL ANALYSIS OF UNITIZED CURTAIN WALL

4.1 General overview of the CBE project

4.1.1 Project introduction

The Commercial Bank of Ethiopia (CBE) headquarters building project is one of the pioneering high-rise building projects in Ethiopia and the horn of Africa making it a landmark and icon for its capital, Addis Ababa. The project has three buildings so-called main tower, conference center, and commercial center buildings. The main tower building is an office complex with 4 Basement, Ground, and 48 supper structure floors with a total height of 209m from the ground, and the low-rise buildings of the podium are 4B+G+7 conference center and 4B+G+8 commercial center buildings.

The building emphasizes the diamond shape on the façade to show the building's shininess in the city by using the different angle reflectance of the glass surface.

Figure 4-1: CBE HQ Building

The total glazed area of the building's curtain wall is around 57,800 m^2 for all buildings and more than 70% of it is located on the main tower building. The building's façade adopts the effect of the diamond cut with complex polylines having inward and outward sloped forms. The other basic feature of the building façade is the attached decorative fins which run vertically from the ground to the roof floor.

4.1.2 Façade type selection

The selected façade type for the project is a half-visible Aluminum framed glass curtain wall. The curtain wall supporting frame is an extruded Aluminum profile with an alloy grade of 6063-T6 and the glazing is a double glazed Insulating Glass Unit (IGU) with Low-E coating. The outer glass is 6mm Heat Strengthened Low-E coated glass and the internal glass is 8mm clear tempered glass with an air gap of 12mm dry air. The decorative fin adopts a 3mm Aluminum plate with steel stiffener supported by the Aluminum mullions.

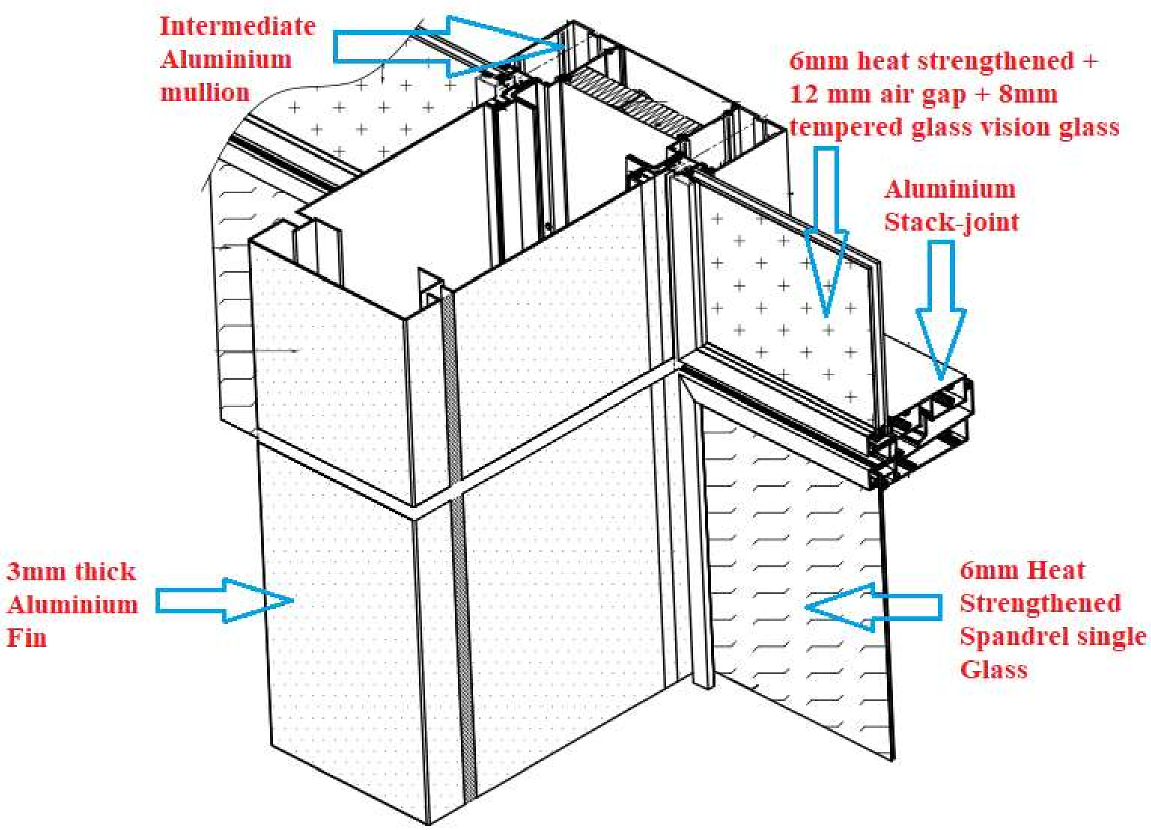


Figure 4-2: CBE HQ curtain wall basic detail

The Unitized curtain wall system is adopted as the building's main façade element except on the ground and the 1st floor, which is a stick-built system, as there are canopies around the building with structural support from the main building structure.

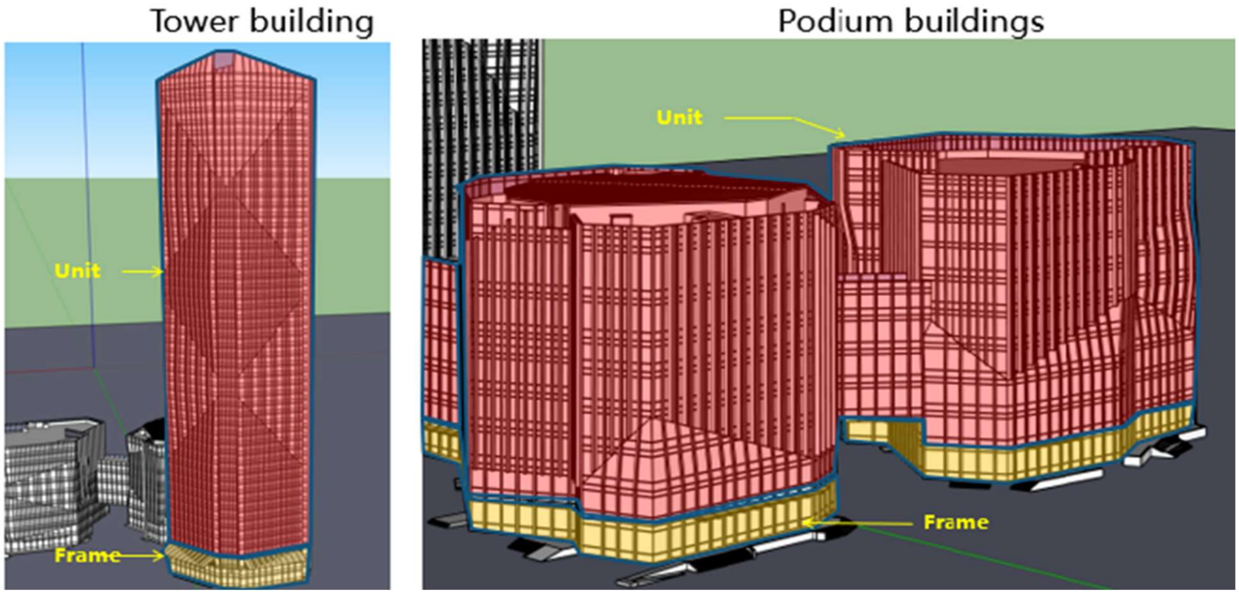


Figure 4-3: CBE HQ unitized and framed curtain wall positions

The main reason for the unitized system curtain wall selection for this project, in addition to accommodation of panel movements due to different reasons, is the high-water leakage resistance requirement due to the inherent nature of the double sheared shape of the façade with potential leakage connection joints. There is heavy rainfall in the project location during June, July, and August which makes the waterproofing requirement of the curtain wall even higher.

The level of quality that can be achieved by using a unitized curtain wall is far superior to the stick-built system in high rise and complex buildings. Due to the complexity of the façade at the diagonal surface and due to the requirement of a high-quality façade for the project, the unitized curtain wall becomes the prime choice.

However, there were two critical challenges while selecting the unit type system for the project. The first one is the decorative fin which needs to be fixed together with the unit panels and the second one is the presence of a diagonal line within the façade which creates both inward and outward slopes in the unit panels. The complexity of this unitized curtain wall is because of these challenges which makes the design and construction difficult.

4.1.3 Design approach

The design approach followed for the unitized curtain wall design of the project is based on the following five key requirements:

1) Aesthetics
2) Structural integrity
3) Performance
4) Constructability and
5) Maintainability

The main aesthetical value of the building is related to the concept of creating a diamond-shaped façade. To achieve this, it requires that some parts of the curtain wall will slope outward and some parts will slope inward. But some unitized curtain wall panels will have both inward and outward slopes within a single panel. Those panels are critical for the decision on the general outlook of the façade during the comprehensive design of the curtain wall system while considering the other design requirements at the same time.

The other aesthetical feature of the façade is the vertical decorative element which extends from the ground to the roof. While designing the unit panels these fins need to be part of the panel. That means the fins will be attached with each unit panel which has the fin as part of the panel and the fins will become discontinuous on each floor. Considerations for structural integrity and maintainability are critical while designing the fins.

While designing the unitized curtain wall of the project taking into consideration of the above listed five requirements, three design approaches were exercised. The main design focus being on how to make the diagonal panels, with both inward and outward slopes in a single unit, to be structurally stable while having a good weatherproof performance.

4.1.3.1 First design approach

The first design approach is to separate the panels at the diagonal line and to make them two panels with their supporting system. The top panel will be supported on the slab above it and the bottom slab to be supported by adding a steel structure that runs along the diagonal line. The steel structure is going to be fixed with the top and bottom slab [refer to Fig. 4-4].

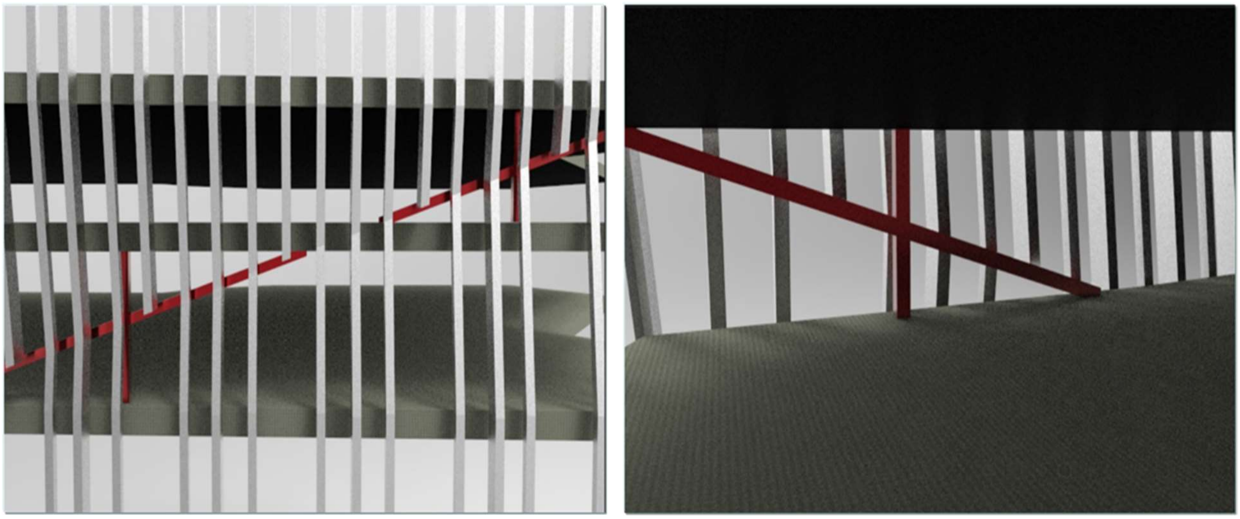


Figure 4-4: Steel beam supported unitized curtain wall design option 3D rendering

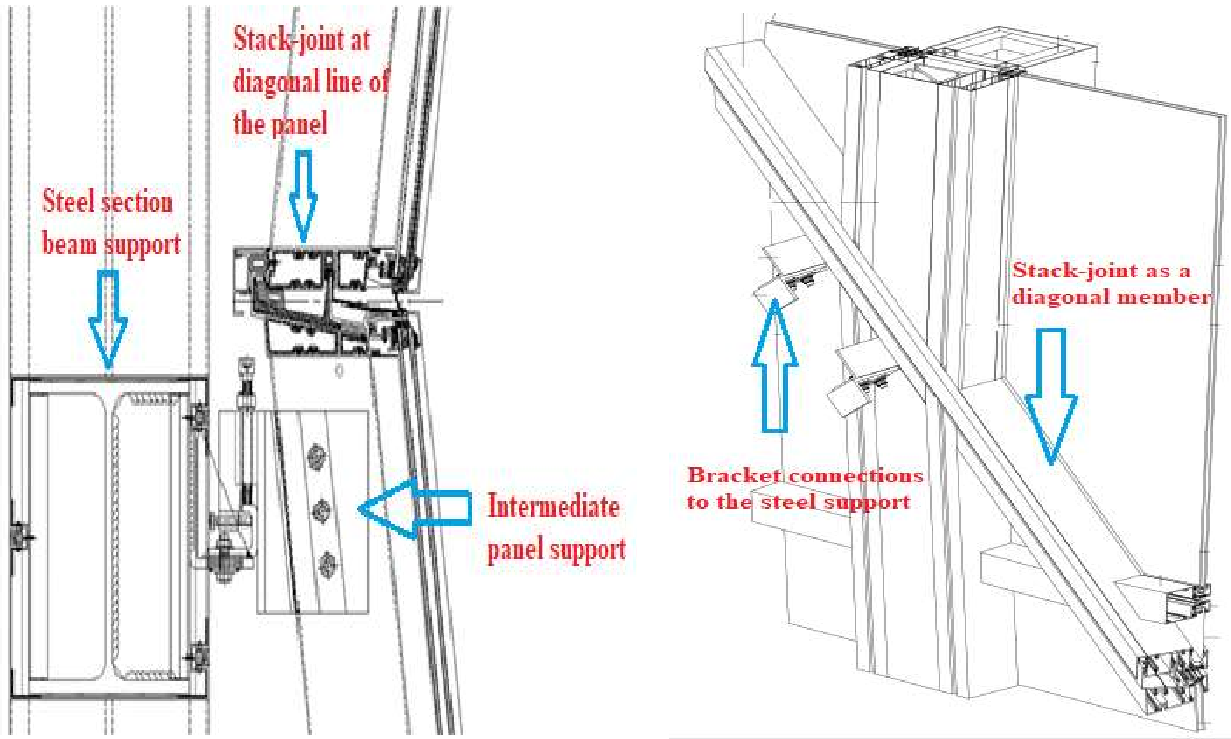


Figure 4-5: Steel beam supported unitized curtain wall proposal section drawing

The first problem with this approach is the aesthetical redundancy created by the supporting steel structure within the interior rooms as it takes some of the office space and also by the fact that another structure obstructs users from accessing or approaching the curtain wall is considered unacceptable.

The other problem is related to the existence of a panel connection at the diagonal line which has a higher risk of creating a loophole for water leakage. The stack-joints are sloped here which means all the water reaching these profiles will be drained down and collected on the bottom panels along the diagonal line instead of draining out of the system.

The design proposal also fails to address how to avoid any racking between the bottom and top parts of the diagonal panels during seismic and wind-induced movements / inter-story drift/. The diagonal steel beam support is proposed to be fixed to the top and bottom slab surface with a slotted connection for some lateral movement allowance. However, the consequence of the relative movement of the top and bottom slabs and the effect of slab deflection due to live load application on the supporting steel beam and the unit panels makes this design approach ambiguous.

4.1.3.2 Second design approach

To resolve the issues raised by the first design proposal, another design approach is presented. This design proposal concealed the diagonal steel support inside the extruded Aluminum profile of the diagonal member and makes it part of the unit panel. In doing so, the diagonal member of the panel is designed as the main load-bearing structure within the panel instead of intermediate mullions. However, it requires another vertical steel support at the end mullion profile of the unit panel for final load transfer to the support brackets.

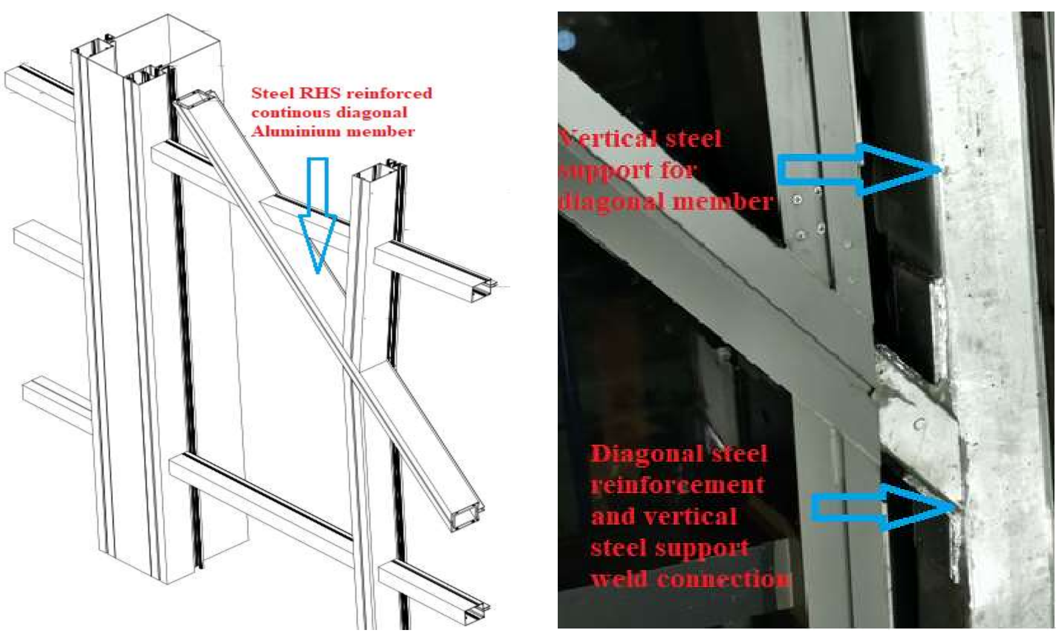


Figure 4-6: Steel reinforced diagonal aluminum member unitized curtain wall design approach

This approach resolves the Aesthetics problem raised in the first design proposal as the steel is fixed inside the diagonal aluminum profile. And also, the waterproof capacity is greatly enhanced as the diagonal member is designed to be a single aluminum profile instead of stack-joints as in the case of the previous design. But most of all, the structural stability of the panels along the diagonal line having both inward and outward sloping is greatly improved.

The other improvement in this design is the diagonal panel becomes a single panel with both inward and outward sloped sections in a single unit. This modification has a positive impact on the lateral movement joint design between consecutive panels for lateral loading or thermal induced movements.

The main drawback of this proposal arises from the difficulty of assembly due to the existence of more steel supports within the unit panels. The steel-to-steel connections within the panel are both bolted and welded connections. The deformation of the steel during welding creates a challenge while inserting and fixing the Aluminum profile which in-turn might affect the quality and waterproof capacity of the curtain wall. On the other hand, the Aluminum profile might also be damaged during the steel welding process. Consequently, a third design approach is required which resolve the issues of difficulties in panel assembly.

4.1.3.3 Final design approach

The final design approach followed for diagonal panels having inward and outward slopes in a single unit panel is to design the mullion as a primary load-bearing structure. However, due to the existence of the joint at the diagonal line of the panel and the surface slope difference, a single mullion cannot be used. Therefore, a mullion connector with good shape adaptability is proposed to be used at mullion connection joints.

This proposal avoids considering the diagonal transom profile as the main load-bearing structure just like in the case of the previous proposals. The interior curtain wall look is boosted aside from the presence of different slopes in a single panel.

The aesthetics, weatherproof performance, ease of constructability, and maintenance requirements appeared to be better addressed in this design proposal. The structural integrity of the system on the other hand has to be properly investigated. With better structural designing of the joints at the mullion connection points, this system is the best choice amongst the three choices.

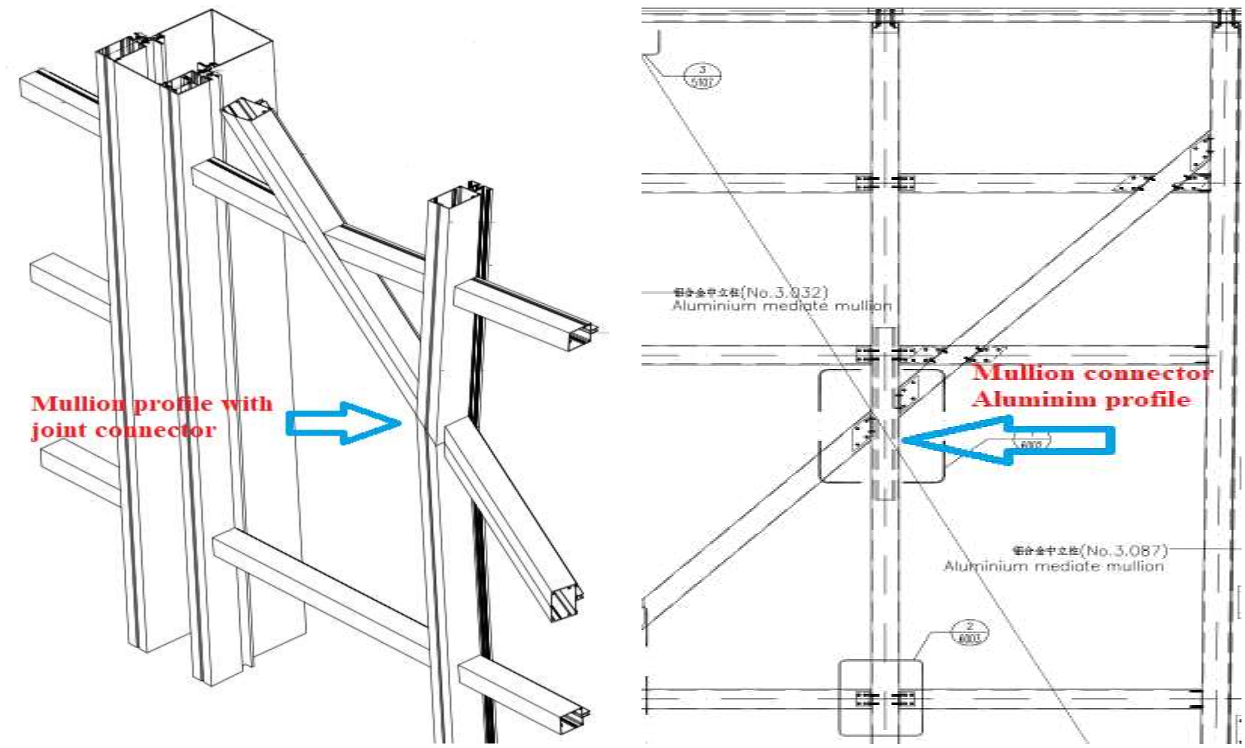


Figure 4-7: Mullion profile joined using Aluminum connector

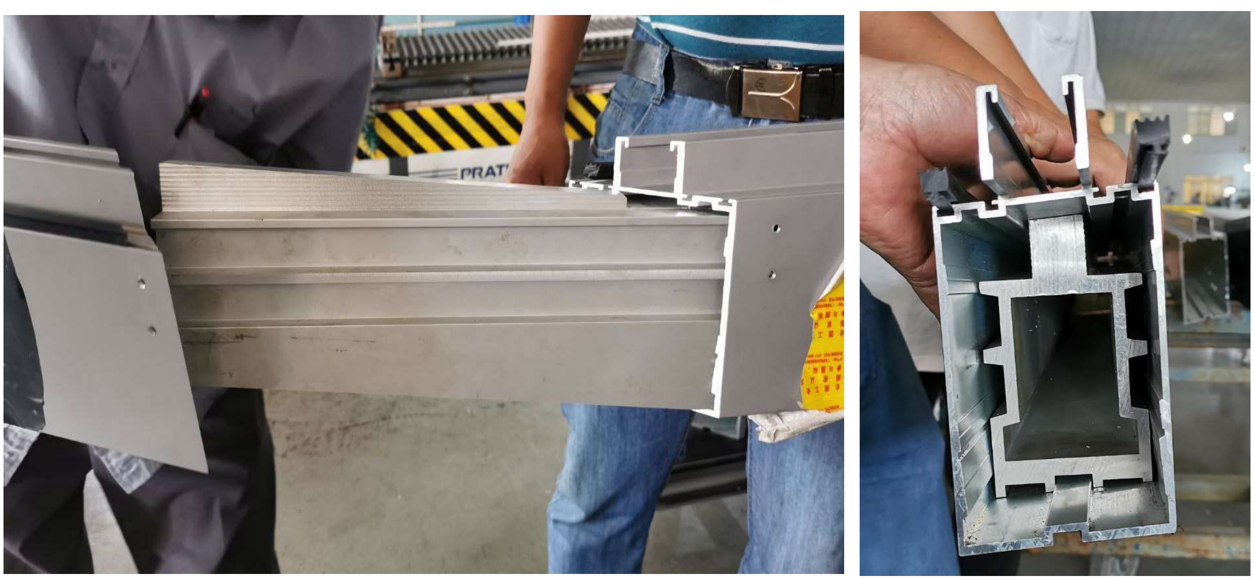


Figure 4-8: Aluminum mullion profile connector

4.1.4 Curtain wall components

The components of the unitized curtain wall of this project are similar to other standard unitized system curtain wall components with the decorative fin attached to the panels.

4.1.4.1 Glazing (infill) panel

The module of the curtain wall is prepared based on the horizontal partitioning of the vision and spandrel panels. The panel partitioning is done every 1200mm including the 300mm wide decorative fins made of 3mm Aluminum plate.

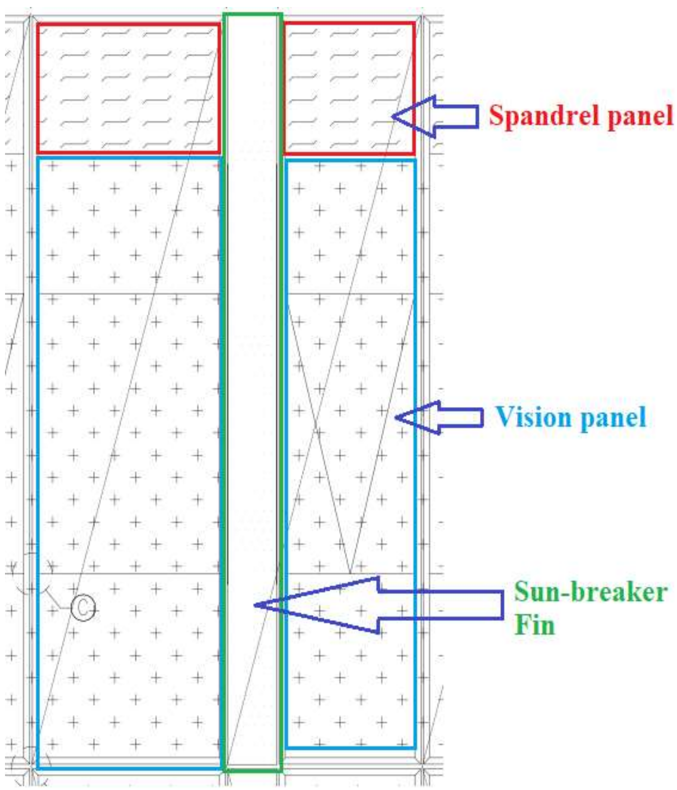


Figure 4-9: curtain wall modulation of the CBE project

Figure 4-10: mini-sample of vision and spandrel panel glasses

4.1.4.1.1 Vision panel

The vision panel comprises of an Insulating Glass Unit (IGU) with double glazed glass. The outer lite is a 6mm heat-strengthened Low-E coated clear glass and the inner lite is 8mm thick tempered clear glass with an intermediate gap of 12mm filled with dry air.

The main reason to adopt the heat-strengthened glass for the outer lite is to avoid visual distortion which is common while using tempered glass even though, tempered glass is twice stronger than that of heat strengthened glass. For a glazed façade with such a larger glazed area, visual distortion on the curtain wall glass has a huge aesthetic impact.

To better address the thermal insulation requirement and to achieve the required shininess of the diamond shape curtain wall, a glass with a single layer of Low-E coating is used for the outer lite.

4.1.4.1.2 Spandrel panel

On the other hand, for the spandrel panel, a 6mm heat-strengthened reflective glass with galvanized steel sheet back panel is used. For larger areas of spandrel panels covering external walls, the glass thickness becomes 10mm according to the structural calculation requirement.

Rockwool insulation material is applied behind the back panel to enhance the spandrel panel fire and thermal insulation capacity.

4.1.4.1.3 Fin

The project curtain wall has two different depths of decorative fins maintaining the same 300mm width. The bigger fin extends by 750mm away from the glass of the curtain wall while the smaller one only extends by 300mm.

The 750mm fin requires a steel truss stiffener to withstand the self-weight and applied lateral loads and to effectively transfer it to the supporting Aluminum frame.

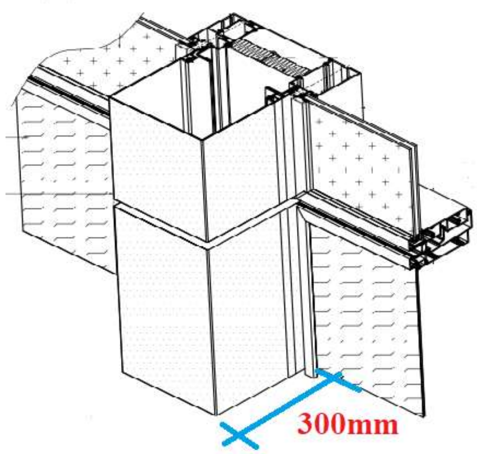


Figure 4-11: 300mm deep fin

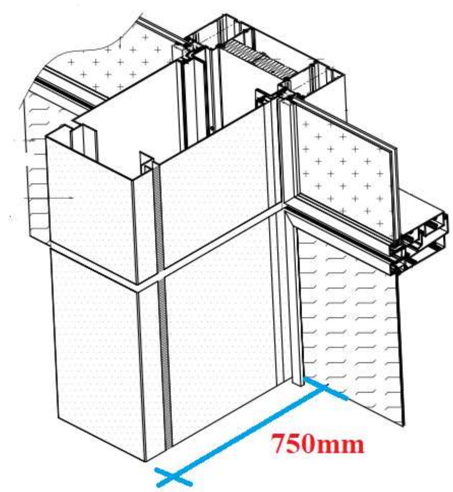


Figure 4-12: 750mm deep fin

4.1.4.2 Glazing system

The curtain wall type of this project is a half-visible frame grid system where the glass is supported mainly by the pressure plate vertically and by structural silicone sealant horizontally. However, structural silicone sealant is also used vertically in addition to the pressure plate although all the load is designed to be carried by the pressure plate.

The pressure plate (Aluminum cup) and the structural sealant bite width and thickness were calculated before the Aluminum profile die drawing and extrusion is done as they have a major impact on the profile design.

The aluminum cup must be designed not to affect the movement tolerance provided between the panels in the unitized curtain wall. Accordingly, in this project, the separate Aluminum cup profiles are used for the adjoining male and female mullions and transoms.

Figure 4-13: Pressure plate (Aluminium cup) detail of unitized curtain wall

4.1.4.3 Load bearing structure (frame)

The main load-bearing structure of the unitized curtain wall is an Extruded Aluminum profile with an alloy grade of 6063-T6. In some special cases where additional structural integrity is required additional Aluminum or steel profile is inserted as a stiffener. For some non-structural members, 6063-T5 grade alloy Aluminum is also used.

The Aluminum profiles are customized profiles that are designed specifically for the project based on the shape of the façade, the structural requirement, and leakage control capability.

E-shaped extruded Aluminum profiles (open type, boxed type, and double-boxed types) are used for the unitized curtain wall of the project. Also, other corners and intermediate closed mullion and transom profiles are used.

To realize the diamond shape of the building façade, the curtain wall is offset by a certain amount (around 3.5˚) inward or outward from vertical. The right and left parts of the slab from the diagonal line are offsetting in different direction when one side goes outward the other go inward. This will create some complexity to use rectangular profiles as the glass cannot be parallel to the slab and also the rectangular profile cannot be perpendicular to the slab.

To resolve such problems, a parallelogram-shaped (including rectangular) profiles were designed for custom profile extrusion. In doing so, not only the glass is kept parallel to the slab but also, the profiles are perpendicular to the slab and the glass.

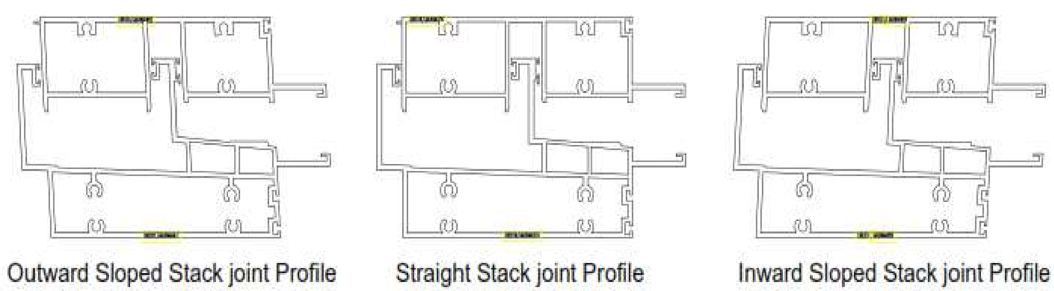


Figure 4-14: different shapes of the stack joint profiles due to double sheared curtain wall

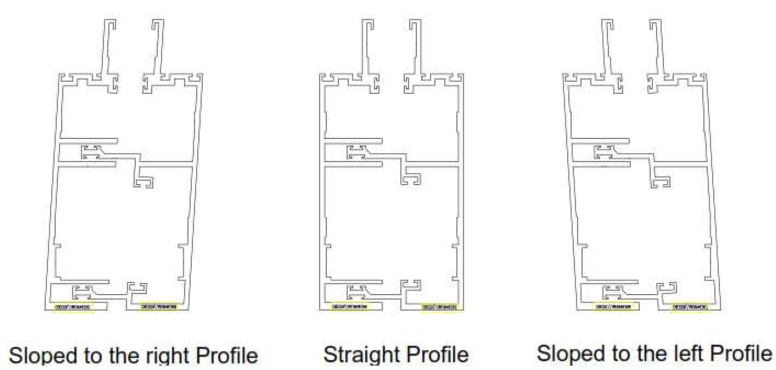


Figure 4-15: different shapes of the open type male and female mullion due to double sheared façade

Powder coating is used for all internal Aluminum profile surfaces and PVDF paint coating for all outside profiles which are exposed to the environment.

4.1.4.4 Brackets

The brackets for the unitized curtain wall are used to hang the panel to the building structure so that the load on the panel can easily be transferred to the building. The bracket plates and C-channels of this building are made of Q235 Galvanized steel.

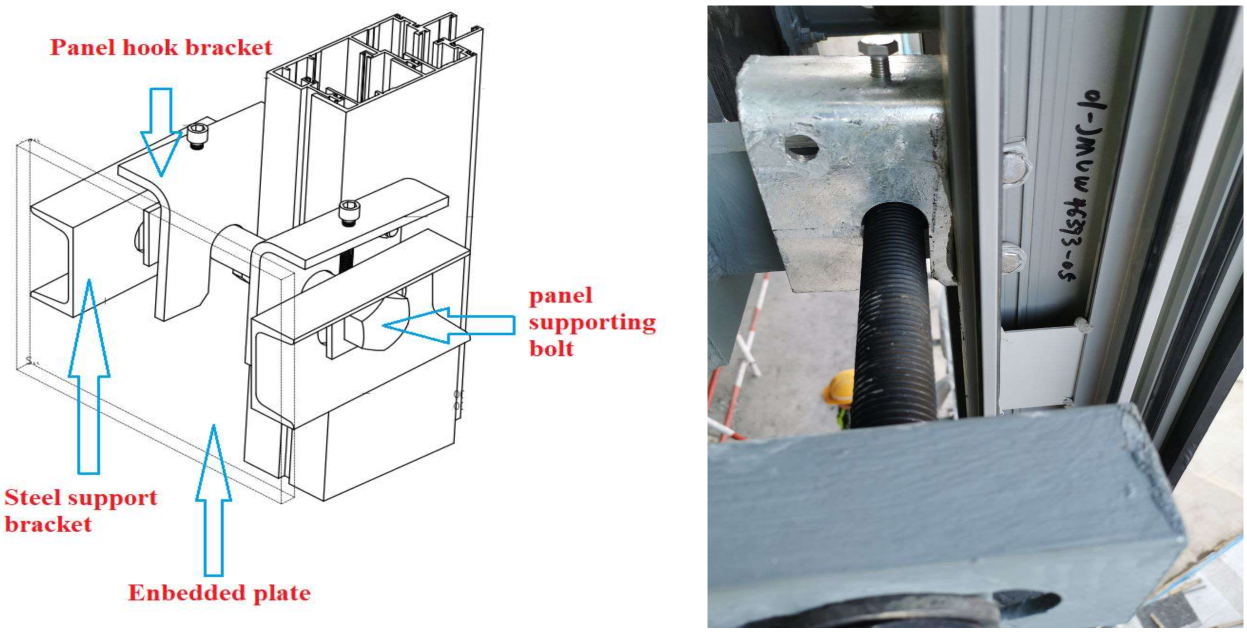


Figure 4-16: Curtain wall supporting bracket

4.1.4.5 Anchor

Embedded plates are used as an anchorage on the reinforced concrete structure so that the C-channel bracket can be welded on it and transfer the load from the curtain wall to the building structure. Since adjustment along the edge beam external surface is restricted for the embedded plate type, the brackets must be on their exact location before welding.


Figure 4-17: embedded plate anchorage for curtain wall support

4.1.4.6 Weather Sealants and gaskets

To avoid air and water infiltration through the curtain wall and to enhance the thermal performance, gaskets and weather sealants are used. The weather sealant is applied where ever we have a joint or connections and a gap to fill.

Accordingly, gaskets are used to fill some gaps and to provide separation between glass and Aluminum by inserting it through the provided groove on the Aluminum profile. Since the aluminum profiles are custom made profiles, all of the gaskets are also custom made for this project specifically. The main gasket used for this project is an EPDM gasket due to its performance when exposed to the environment. However, those parts where the gasket and structural silicone sealant are in contact with silicone gaskets have been used to get a good bondage between the sealant and the gasket.

4.1.5 Performance Mockup specimen selection

The test specimen selection for full height curtain wall laboratory test must consider the part of the curtain wall which represents the majority of the façade area to check against the structural and performance adequacy. As much as possible the test specimen must also include complex and special parts of the wall which might affect the test output.

For the CBE building unitized curtain wall performance test, the test specimen selection considers the following crucial factors to be included as much as possible.

a) The diagonal line that divides the outward and the inward tilted panels.
b) The decorative element fin (both sizes of 750mm and 300mm depth)
c) The curtain wall panel at the larger floor to floor height to design the Aluminum profile for the largest unsupported length.
d) The larger area of glass for both vision and spandrel panels
e) Corner panels
f) Multiple panels and multiple floors

Each compartment length is 1200mm, but most panels are set with 2400mm width for rapid construction. the test specimen adopts 3 panels (with 2400mm panel width) on the front and one corner panel at the edge for three floors. Although it is difficult to find a test specimen that includes all the above-mentioned factors, the selected specimen includes almost all of them.

The selected test specimen as Figure 4-18 has the diagonal line and tilted panels including the fins of both sizes. The larger floor to floor height of the unitized panel 4300mm is adopted for the top two floors and the typical 3800mm floor height for the first floor.

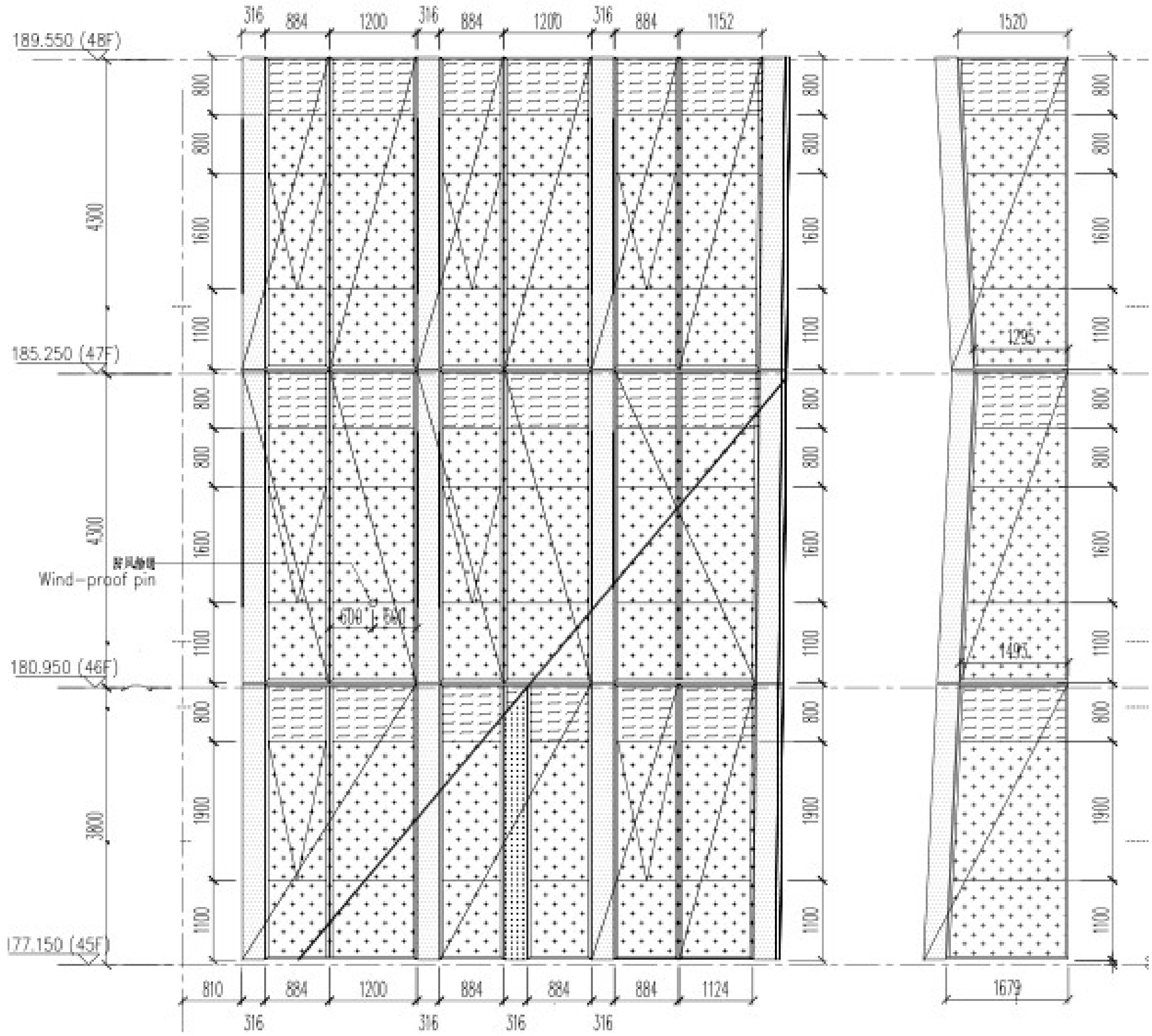


Figure 4-18: The selected test specimen of unitized curtain wall

4.2 Design loads

4.2.1 Wind load

The design wind load value for curtain wall design of the CBE HQ building is determined by using a High-Frequency Pressure Integration (HFPI) wind tunnel test that was conducted by the Space Structure Research Center, School of Civil Engineering, Harbin Institute of Technology, China. The main reason to choose wind tunnel tests over the conventional building code provisions is the irregularities in the plan shape of the tower building (Bitsuamlak & Bezabeh, 2017).

To represent the building structure on the wind tunnel testing rigid building models made of Acrylonitrile-Butadiene-Styrene (ABS) were used with a geometric scale of 1:250 (keeping the blockage ratio under 5%).

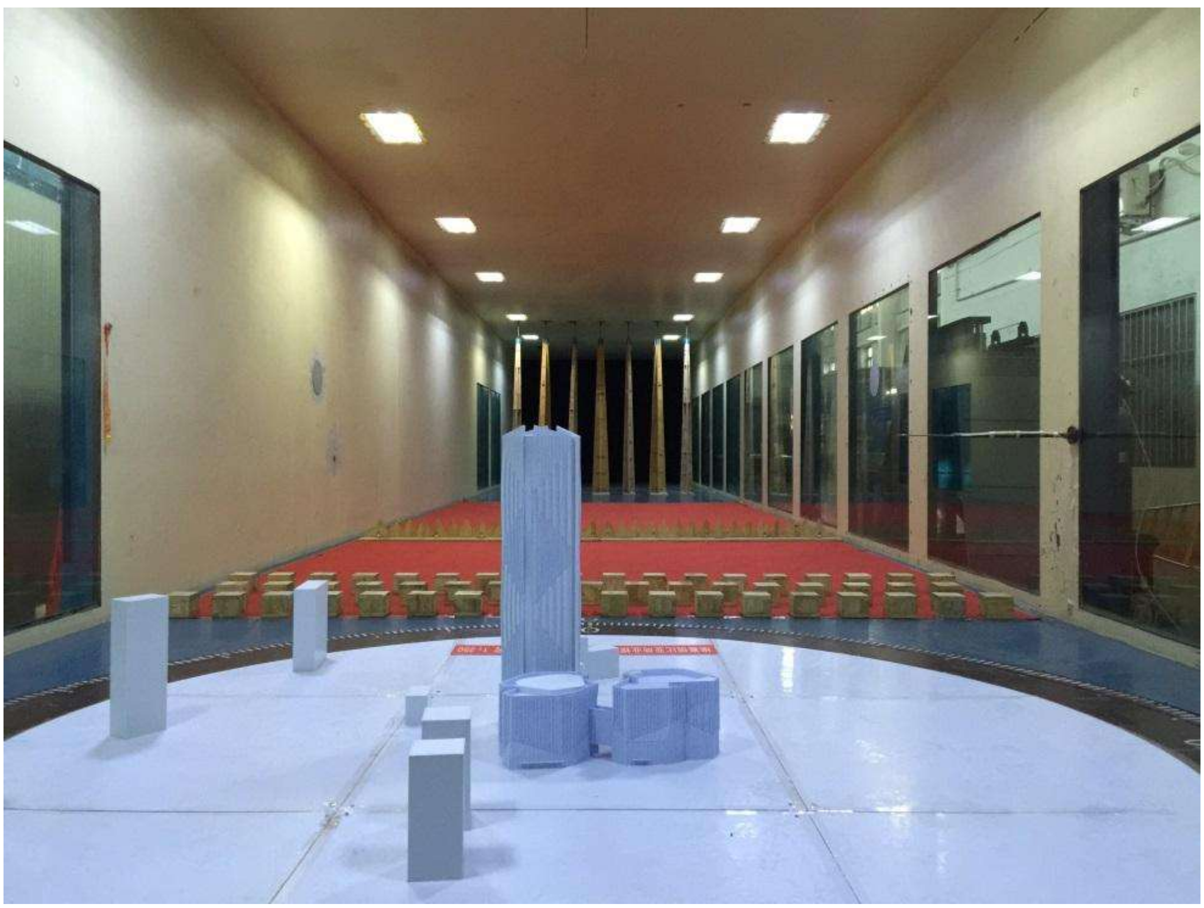


Figure 4-19: CBE HQ project rigid model in the wind tunnel test chamber

A wind climate analysis is performed based on the meteorological data collected from 1975-2016 at the Addis Ababa Bole International Airport. Accordingly, considering 50-years of data (with 10 minutes average) at 10 m height in open terrain the design wind speed of the project is selected to be **35m/s**.

A total of 294 pressure taps were attached to the tower building of which 36 were in the parapet wall section. Based on the data collected from the pressure gauges and performing the rechecking calculation, the design wind loads on the cladding (curtain wall) are identified and presented for each face of the façade as shown in Figure 4-20.

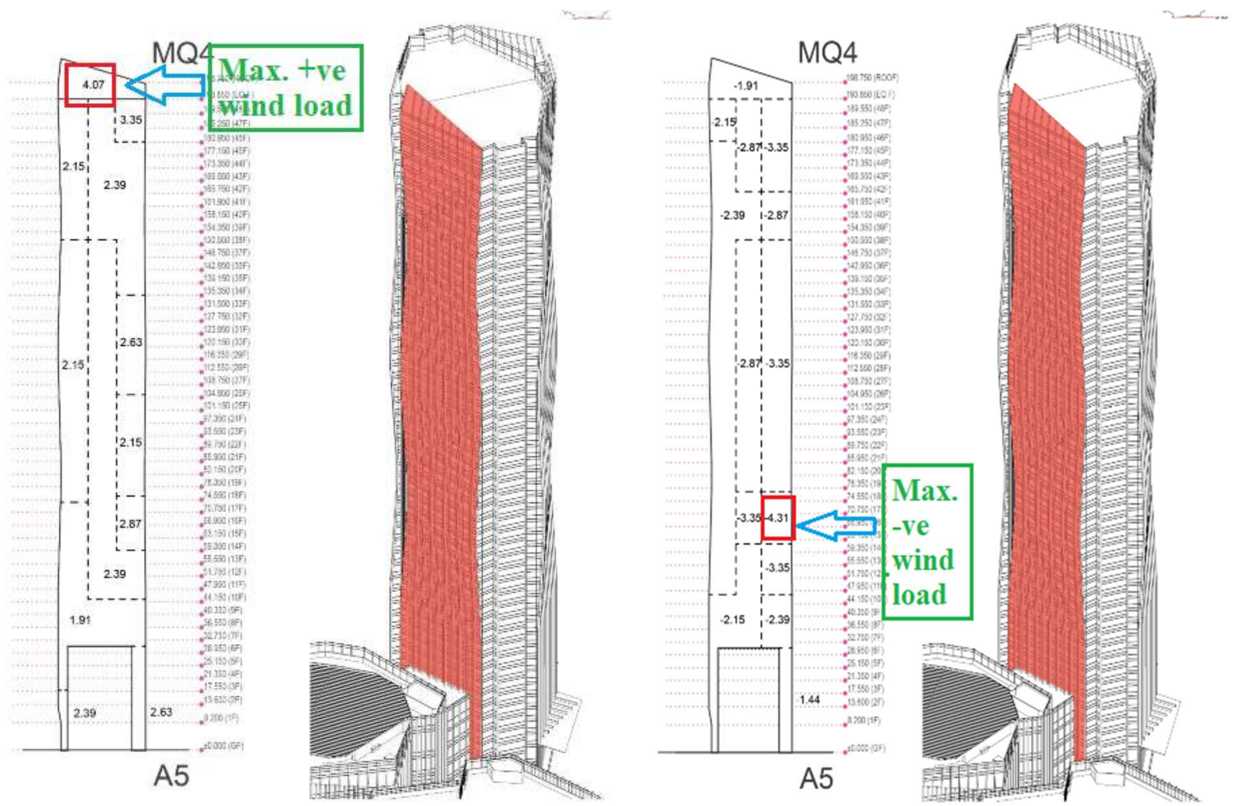


Figure 4-20: Positive and negative design wind loads on curtain wall based on the wind tunnel test output

Accordingly, the following maximum design wind loads are recommended for curtain wall detail designing:

1) The largest positive wind load for the design of tower unitized curtain wall is **+4.07 KPa**.
2) The largest negative wind load value for the design of all tower unitized curtain wall is **-4.31 KPa.**

4.3 Finite Element Modeling

The Finite Element Analysis of the selected Performance Mockup Unit (PMU) structural analysis is done using SAP 2000 version 21. The Finite Element Analysis comprises of modeling and analyzing the PMU model which exactly represents the test specimen.

Although the analysis can be done for both serviceability and ultimate limit states, the focus of this paper is only for the serviceability check of the structural analysis. The serviceability limit state checking is done for the deflection check of the continuous mullion members and the joined mullion members.

The following sub-sections show the steps followed in modeling and analyzing the selected specimen.

4.3.1 Material Definition

The Aluminum profile material property in SAP 2000 version 21 software is inbuilt within the software for both Aluminum grades 6061-T6 usually used for support hook and 6063-T6 which is widely used for Aluminum mullion and transom profiles of curtain walls.

The steel materials are also defined in the SAP 2000 software with the inbuilt material properties. Chinese GB standard is used for the steel grades of Q235 and Q345.

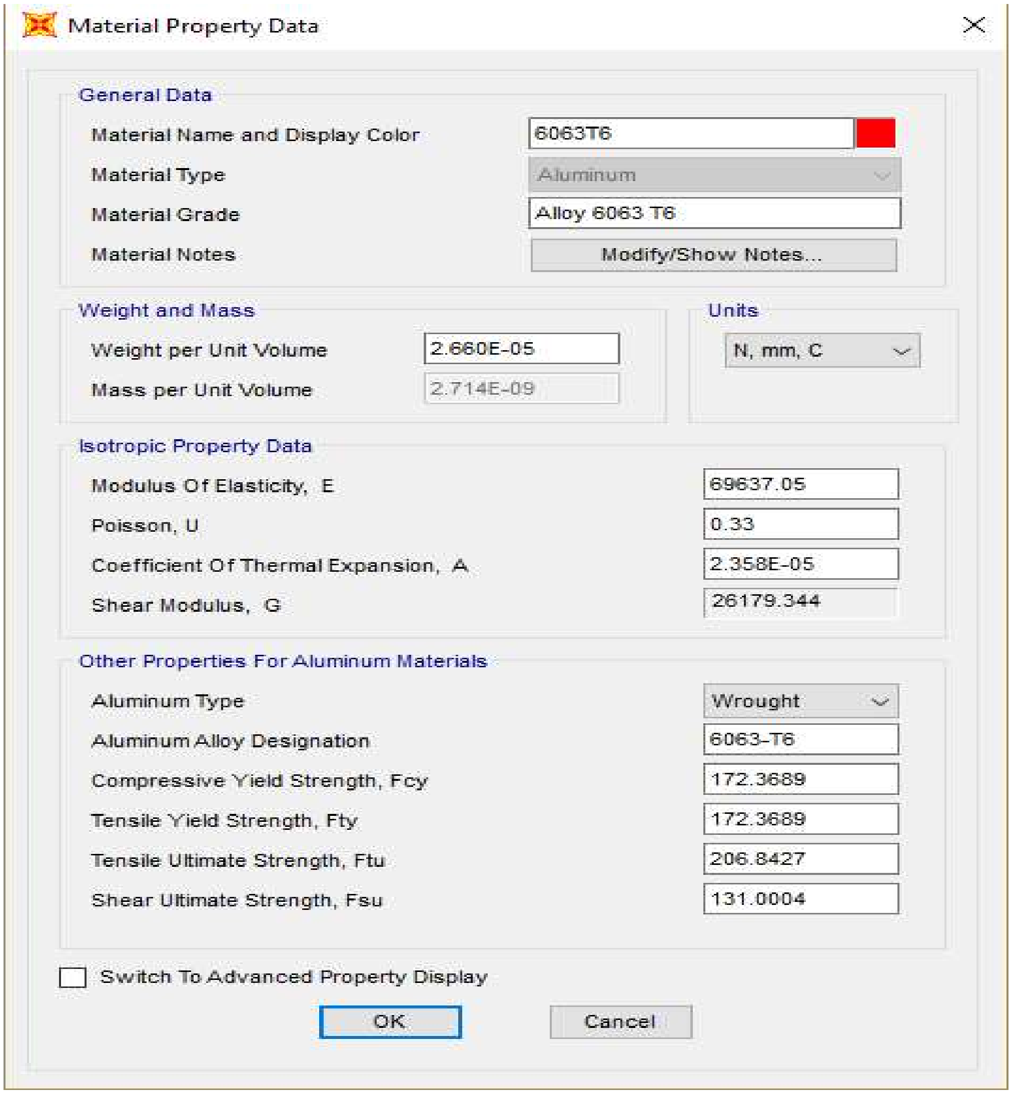


Figure 4-21: Aluminum profile material properties

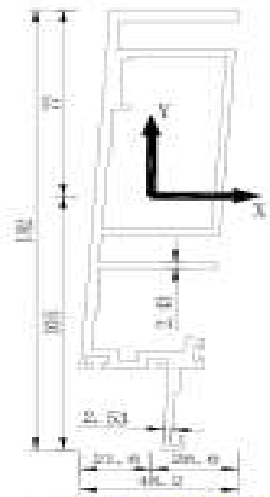
4.3.2 Section Properties Definition

Extruded Aluminum profiles have a very complex cross-section which creates additional challenges in accurately modeling the frame in SAP 2000 software. The unitized curtain wall male and female profiles of mullion and the stack joint profiles of the transom especially are difficult to design as they are.

The common practice is to design the profiles as a rectangular or other section with similar section property of the summed-up section (male + female profiles) of the frame member. Especially the Moment of Inertia of the representing rectangular section is set to be similar or a bit lower than that of the summed-up section property.

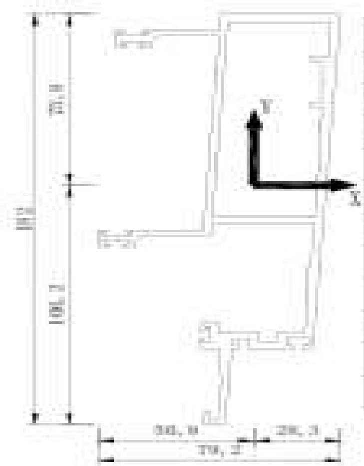
For instance, the section property of one of the mullions with a male and female sections (MU1) is as shown in Figure 4-22.

Female section



MASS PROPERTIES(UNIT)	VALUES
Area(mm2)	1457.44
Perimeter(mm)	950
Bounding Box – X (mm)	-21.58 to 26.57
Bounding Box – Y (mm)	-104.99 to 77.0
Centroid – X (mm)	0.00
Centroid – Y (mm)	0.00
Moments of inertia – X (mm4)	4256887.61
Moments of inertia – Y (mm4)	297609.25
Product of inertia – XY (mm4)	-157101.23
Radii of gyration – X (mm)	54.04
Radii of gyration – Y (mm)	14.28

Male section



MASS PROPERTIES(UNIT)	VALUES
Area(mm2)	1511.28
Perimeter(mm)	1055.47
Bounding Box – X (mm)	-50.9 to 28.25
Bounding Box – Y (mm)	-106.24 to 75.75
Centroid – X (mm)	0.00
Centroid – Y (mm)	0.00
Moments of inertia – X (mm4)	4394475.21
Moments of inertia – Y (mm4)	635263.44
Product of inertia – XY (mm4)	-137124.91
Radii of gyration – X (mm)	53.92
Radii of gyration – Y (mm)	20.5

Figure 4-22: Aluminum profile section properties

The combined section property used for the model is calculated by summing up the correlating properties of the two profiles, specifically their moment of Inertia.

$I_{x\ combined} = I_{x\ female} + I_{x\ male} = 4{,}256{,}887.61mm^4 + 4{,}394{,}475.21mm^4 = 8.65\ x10^6mm^4$

$I_{y\ combined} = I_{y\ female} + I_{y\ male} = 297{,}609.25mm^4 + 635{,}263.44mm^4 = 9.33\ x10^5mm^4$

The modeled cross-section for the mullion is shown in Figure 4-23.

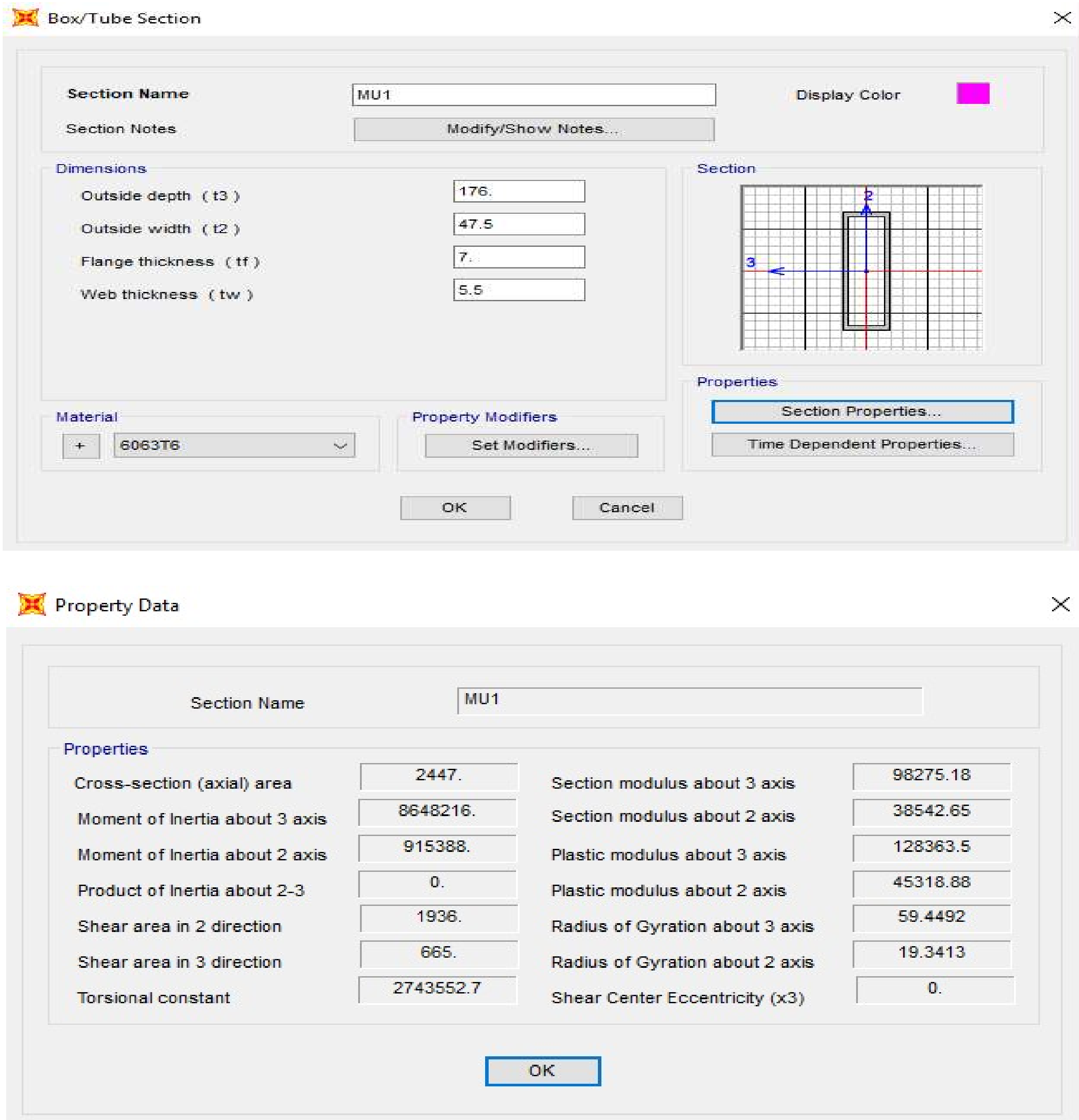


Figure 4-23: Aluminum mullion cross-sectional properties on the SAP model

Similarly, all members of the Aluminum frame are modeled including the stack joints. Although the modeling of the Aluminum members using an equivalent section might give closer results to the actual profile, but the relative movement of the male and female profiles is not considered. This effect can be greatly noticed on the stack joint profile where the inter-story drift and the lateral in-plane movement are accommodated.

The Unitized panels which have two different slopes (inward and outward) is the critical panel. Consequently, the mullions supporting the diagonal members will have discontinuity somewhere in the span and a single mullion cannot be used. Another Aluminium stiffener is inserted inside the mullion member at the connection join location to make a single joined mullion to span a single floor.

As one part of the focus area of this paper, the connection details on the model at this location are required to resemble as much as possible with the design and the test specimen. Accordingly, the section properties of the intermediate mullion and the 800mm long stiffener aluminum section are summed-up and applied at the joint with the corresponding section as shown in Figure 4-24.

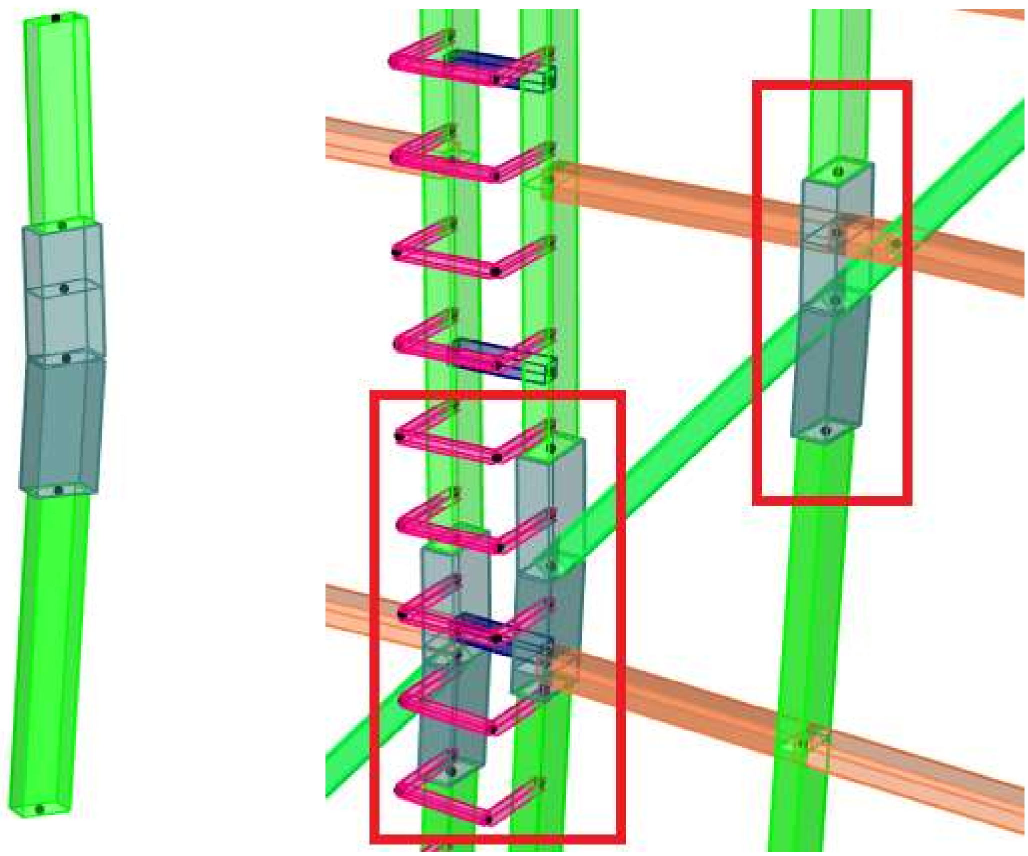


Figure 4-24: Joined mullion profiles detail with increased section properties on the SAP 2000 model

The final model of the curtain wall is shown in Figure 4-25 which incorporates the Aluminum profile mullion and transom members including the diagonal transom, and the steel fin stiffeners attached to the intermediate mullions. The glass and the Aluminium plates are not included in this model but the self-weight and applied loads on them is calculated and applied on the supporting frames directly.

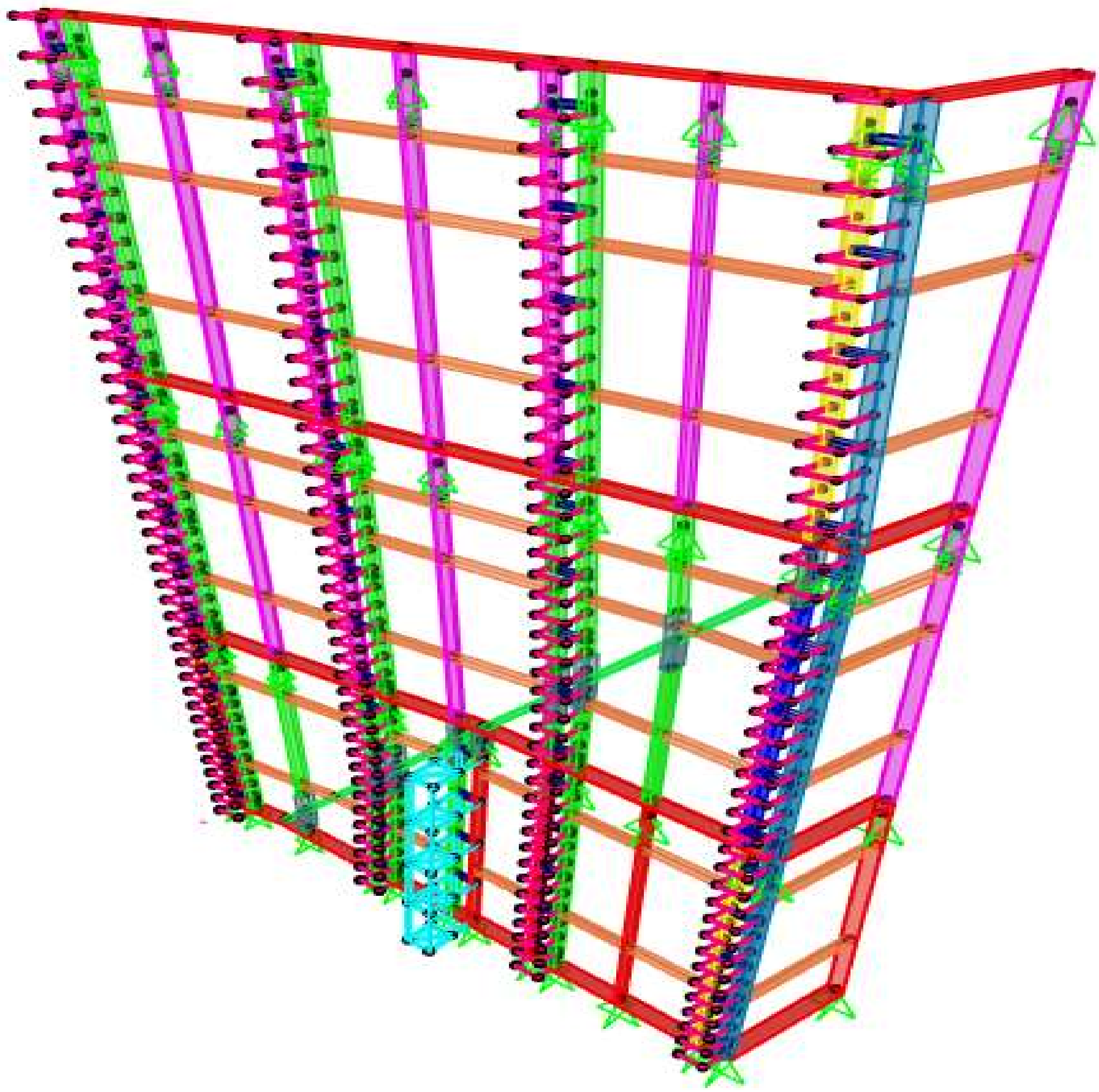


Figure 4-25: The unitized curtain wall designed SAP model

4.3.3 Frame releases

The members are released at the joints of mullion and transom as the connection mechanism used is a bolt connection. The mullion and transom members that span full length are released on either end for Axial load and Torsion while moments (M2 and M3) are released on both ends.

For the joined mullion members, the release is applied at the floor connection levels as the other mullion sections and not released at the joint location to avoid the occurrence of a mechanism.

4.3.4 Load applications

4.3.4.1 Dead load application

The self-weight of the Aluminum frame and steel fin support is calculated by the software itself. Only the dead load of glass and Aluminum plates used as a decorative element including their accessories are loaded onto the model.

The glass dead load is applied as a point load at one-fourth of the transom length from both ends at the location of setting blocks. On the other hand, the dead load of the Aluminium plate is applied as a uniformly distributed load in the gravity direction.

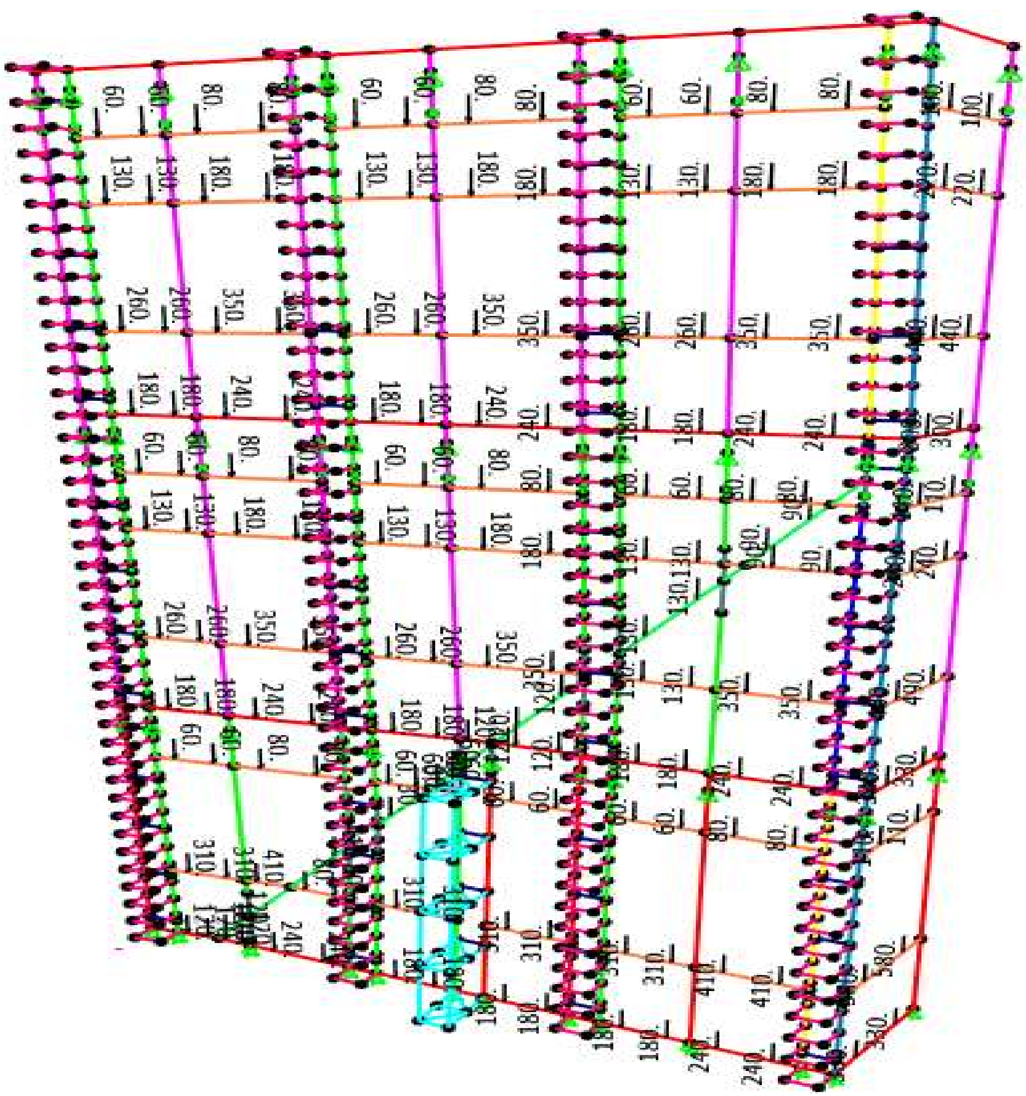


Figure 4-26: Applied dead load on the unitized curtain wall model

4.3.4.2 Wind load application

The wind load shared by each profile from the glass based on their tributary area is calculated and applied directly to the Aluminum mullion and transom normal to the frames. The tributary area of the members to the applied wind pressure on the glass is calculated similarly as the yield line concept of slab. The pressure and suction wind loads are applied separately in their respective directions on the model.

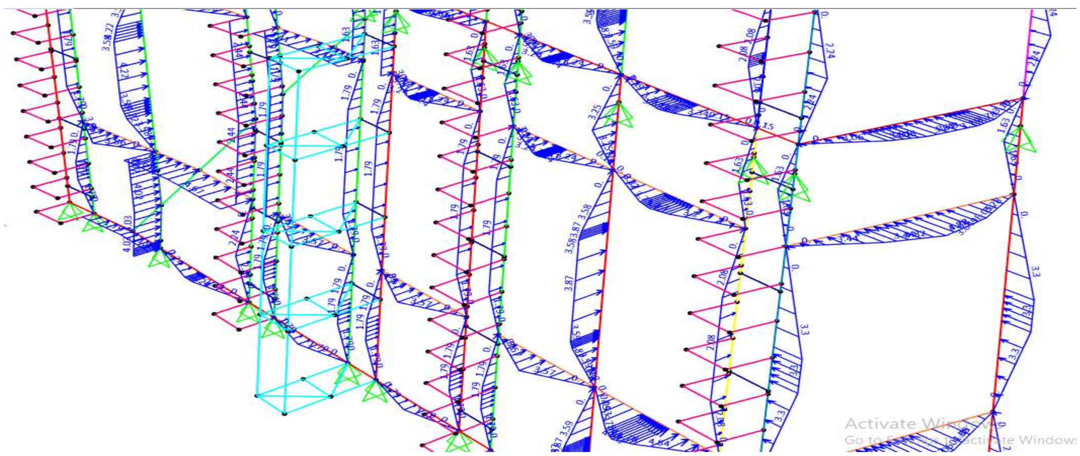


Figure 4-27: Applied wind load (+ve) on the unitized curtain wall model based on the tributary area

However, due to the difficulty to quantify the load shared by all the perimeter supporting members at the diagonal member location a more conservative approach is followed. For the mullion and transom members having joints within the span, the load is applied as a uniform load instead of calculating based on their tributary area.

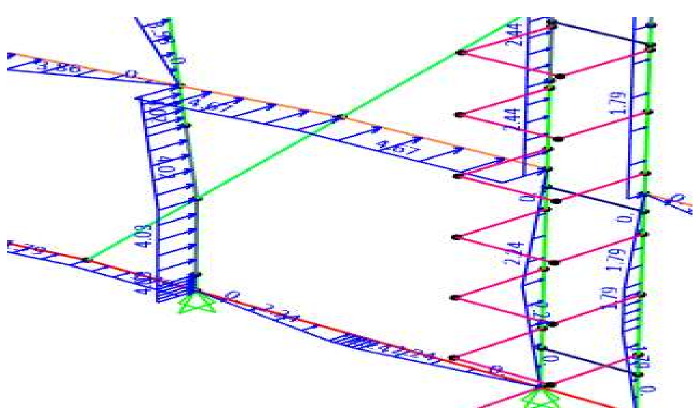


Figure 4-28: Applied uniform wind load on the joined members within the span

The wind load on the Aluminium plate decorative fins is also calculated and applied directly to the supporting steel members.

4.3.5 Load combinations

The load combination used for the analysis is done in conformance with the test load applications. The tests are conducted for both serviceability and ultimate limit states using the standard test procedure and the design has been done with the corresponding load combinations. However, for the sake of this paper, the load combinations are set as per the requirements of the thesis scope. Accordingly, the model is only checked for the serviceability limit state.

For the structural performance design check at the design wind pressure, both pressure and suction, the load magnification safety factor of the ultimate limit state is not used during load combination. Rather, the design wind pressures are set at 25%, 50%, 75%, and 100% in different combinations so that it will be easier to cross-check with the results of the test at the Serviceability limit state.

The following are the load combinations used on the SAP 2000 curtain wall model:

1. COMB1 = DLgl + DLa-p
2. COMB2A = COMB1 + 0.25WLp
3. COMB2B = COMB1 + 0.25WLs
4. COMB3A = COMB1 + 0.5WLp
5. COMB3B = COMB1 + 0.5WLs
6. COMB4A = COMB1 + 0.75WLp
7. COMB4B = COMB1 + 0.75WLs
8. COMB5A = COMB1 + WLp
9. COMB5B = COMB1 + WLs
10. COMB6A = COMB1 + WLp + WLp-steel
11. COMB5B = COMB1 + WLs + WLs-steel

Where, DLgl = Glass dead load, DLa-p = Aluminum plate dead load, WLp = Wind load (pressure), WLs = Wind load (suction), WLp-steel = Wind load (pressure on steel), and WLs-steel = Wind load (suction on steel).

4.3.6 Deflection limits

The serviceability deflection limits for Aluminium profiles and glass is set to the following values:

I. For wind load:
   a. Aluminum Frameworks (supporting Single glazing)
      Span/175
   b. Aluminum Frameworks (supporting Double glazing)
      i. ***Span/200*** for spans less than 3m
      ii. ***Span/300 +5mm*** for spans in between 3m and 7.5m
      iii. ***Span/250*** for spans larger than 7.5m
   c. Glass center deflection limit
      Span/60 or ***25mm***, whichever is less

II. For Dead Load:
   a. Aluminum Frameworks
      Span/500 or ***3mm***, whichever is less

4.4 Finite Element Analysis

The designed unitized curtain wall model is then analyzed by running the analysis for the aforementioned loads and load combinations for the serviceability structural check of deflection.

5 FULL-SCALE TEST OF UNITIZED CURTAIN WALL

5.1 Introduction

The full-height unitized curtain wall test specimen is constructed and tested in the laboratory called "Guangdong Construction Engineering Quality and Safety Testing Head Station co., LTD" Guangzhou, China. The institute has "L" shaped extra-large type multifunctional curtain wall test equipment with the dimension of (18+8) m in width and 22m in height. This gives the institute the ability to test extra-large curtain wall specimens even with irregular shapes.

Figure 5-1: Curtain wall testing chamber

Three floors of curtain wall specimen are selected for the test with the overall test specimen size of (7435+1990) mm width including the corner panel and 12,400mm height. The top two floors story height is 4,300mm and the bottom floor is 3,800 mm high.

Figure 5-2: Curtain wall installed test specimen

5.2 Test specimen assembly

Since the specimen includes a corner panel and also inward and outward sloped panels due to the diagonal line, additional support made of steel I-sections is extended to the existing test chamber. The steel support is designed by the test institute ensuring that any structural deformations or loads from it won't be transferred to the curtain wall specimen.

The steel structure frame provides support to the curtain wall's support brackets. The maximum vertical space between two support brackets is 3,810mm as additional supports were introduced to the 4,300mm story height to minimize the deflection under service load.

The test specimen assembly started by welding the Curtain wall support bracket on the steel structure after finishing surveying setting out work. All the brackets are welded and checked before panel installation begins as it requires a higher level of precision for a smooth panel installation.

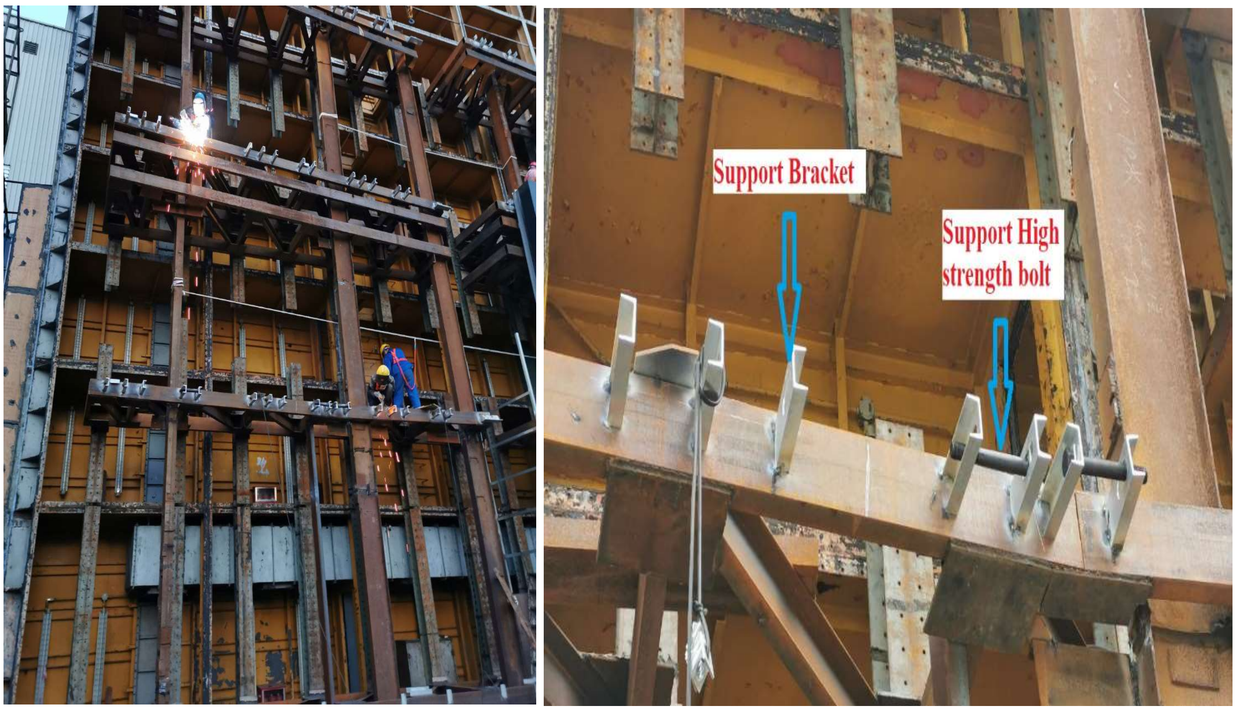


Figure 5-3: Curtain wall support bracket and High-strength bolt welding

The bottom gutter supporting bracket is different from the other panel supporting brackets as the gutter is laid /fixed/ on it first instead of hanging on it. The Aluminum stack joint (gutter) is then fixed, leveled and the gaps are sealed with sealant to avoid water leakage to the inside part of the test chamber. The connection at the corner and at the sharp joint where the diagonal panel would be installed is done with great care as it is a weak point for water leakage and possible connection failure (detachment).

Figure 5-4: Bottom Gutter fixing and weather sealing

After all the bracket and the bottom gutter profile is fixed and checked, the panels are installed in place. During the curtain wall panel test specimen installation, the biggest challenge comes from the panels at the diagonal line and the decorative element alignment.

The decorative element at the diagonal panel is fixed on-site instead of being assembled in the workshop.

Figure 5-5: Unitized curtain wall test specimen installation

The curtain wall is supported by hanging the steel hook, attached to each panel, on the high-strength bolt fixed on the C-channel steel bracket. For the larger panels located at the 4,300mm floor to floor height, additional support is provided to limit the deflection caused by the wind load applied perpendicular to the surface but free to move in-plane and in the vertical direction.

Figure 5-6: Additional supporting bracket

One side of the curtain wall support hook of each panel is equipped with an anti-walk (restraining steel section) to avoid permanent horizontal displacement of panels.

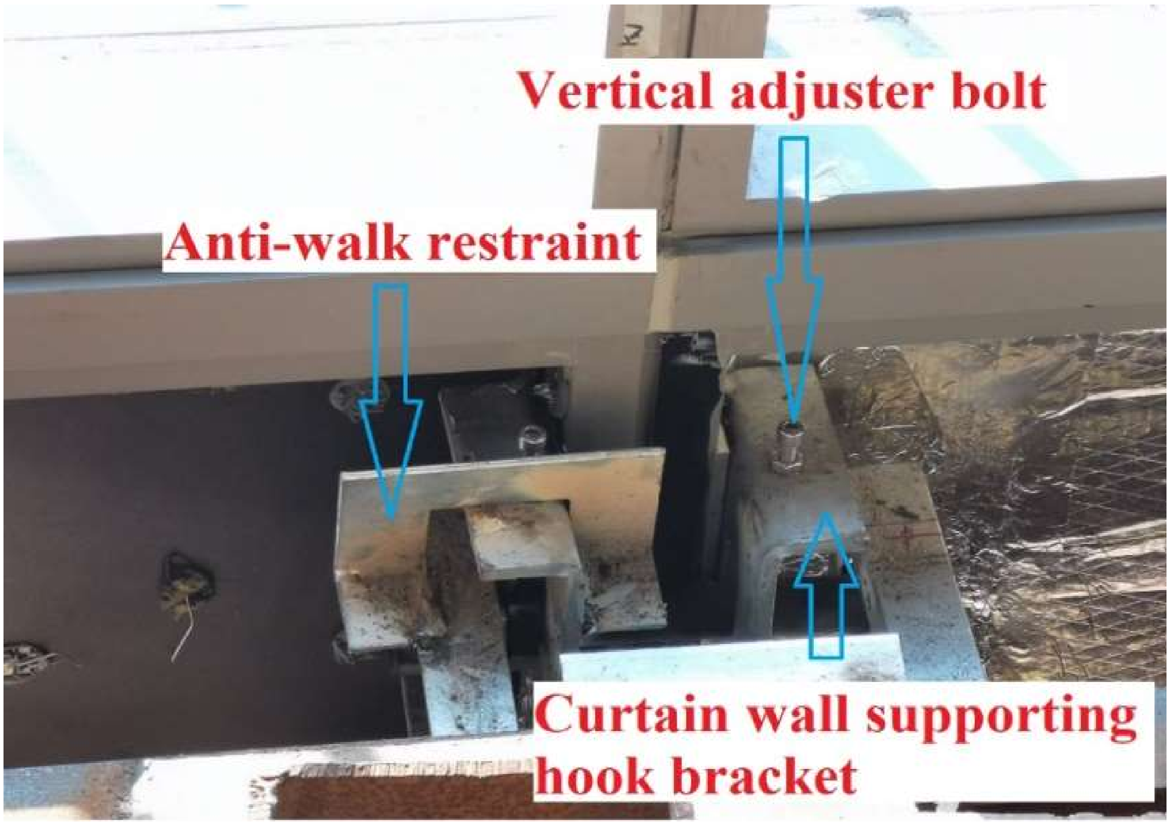


Figure 5-7: Anti-walk used on curtain wall supporting hook

All the panel installation is checked against the design and the chamber is closed using a wooden cover around the perimeter. However, to avoid direct contact between the specimen and the chamber sealing wooden cover, a special type of flexible fabric that doesn't allow water and air leakage is used in between.

The wooden cover and the flexible fabric both checked for any holes and sealed using weather sealant to avoid the adverse effect on the test.

Figure 5-8: Chamber sealed using wooden cover and flexible fabric

5.3 Test setup

As the multiple floor and full height unitized curtain wall test is done for the project's curtain wall performance checking purpose, the test setup of the specimen is to check whether the proposed curtain wall fulfills all the test requirements. Accordingly, the test setup described here also tries to show the overall test setup instead of only focusing on the structural aspects which are the core of this thesis paper.

For this unitized curtain wall specimen performance test, the test procedure and test Items suggested on the American standard AAMA 501.4-09 is implemented with minor project-specific adjustments. Therefore, the following test procedure is adopted:

1. Preloading and Pre-testing (50% of the design wind value)
2. Air Leakage Test
3. Water Penetration Test (Static)
4. Water Penetration Test (Dynamic)

5. Structural Performance Test at Design Wind Pressure
6. Repeat Air Leakage Test
7. Repeat Water Penetration Test (Static)
8. Seismic Movement Test at design displacement
9. Repeat Water Penetration Test (Static)
10. Thermal Cycling Test
11. Repeat Water Penetration Test (Static)
12. Structural Performance Test at 1.5 x Design Wind Pressure
13. Seismic Movement Test at 1.5 x design displacement
14. Water Penetration Test after cutting the outer sealing tape

To be more focused on the test setup of the structural tests of the curtain wall specimen, the test setups are grouped into two parts as shown below:

1) Architectural (functional) tests setup and
2) Structural tests setup

5.3.1 Architectural (functional) tests setup

The architectural (functional) tests group, for the sake of this paper only, are tests that focus on the performance of the curtain wall for weather-related requirements such as air, water, and temperature controls. From the test lists described above, the air and water leakage tests and thermal cycling tests are categorized in this group.

5.3.1.1 Air Leakage Test setup

To test the curtain wall specimen for air leakage test, a source of air supply or exhaust is mandatory. The air supply/ exhaust machine uses an electric power supply of 380V and 75KW. The maximum attainable rotational speed is 2,900rpm and can generate a full pressure of 14,546Pa and a flow of 11,649m^3/h.

Figure 5-9: Air supply and exhaust machine

The supplied or the exhausted air is carried to or from the chamber using a duct that is pre-installed within the test chamber. The duct has an opening and closing airflow controlling access.

Figure 5-10: Air supply and exhaust duct for curtainwall test

A differential pressure transmitter is used to measure the air pressure difference between the chamber and the outside environment.

Figure 5-11: Differential pressure transmitter used to measure air pressure difference

5.3.1.2 Water Leakage Test setup

For the water leakage test, the supply of continuous water spray with the consistent pressure and volume must be guaranteed. The water sprinklers used for the test are arranged as per the standard ASTM E-331 with the spacing of the nozzles being 600mm both vertically and horizontally. The distance between the curtain wall specimen and water sprinkler is also set to 600mm.

Figure 5-12: Fixed water sprinkler

A digital gauge that is used to measure water flow is installed along the water supply pipeline. The water spray system used in this test was set to deliver 3.4 liters/min/m^2 of water although the facility has a capacity of 4.0 liters/min/m^2.

Figure 5-13: Water gauge

For the static water leakage test as it requires air pressure difference between the inside and the outside environment, the air pressure supply system used for the air leakage test is set as per the standards air pressure difference.

On the other hand, for dynamic water penetration tests, an aircraft propeller is used to create the equivalent static air pressure difference on the specimen. The propeller uses an electric power supply of 380V and 250KW which can create a maximum wind speed of 45m/s with the propeller rotational speed of 2,850rpm.

The distance between the propeller and the curtain wall specimen glass is 2500mm and at the center of the front face of the curtain wall.

Figure 5-14: Aircraft propeller for dynamic water penetration test

5.3.1.3 Thermal Cycling Test setup

The test setup of the thermal cycling test is done in the middle of the testing process as it is done after the completion of air leakage, water leakage, and serviceability limit tests of the structural and Inter-story drift tests. Before placing the insulated chamber in place, the water sprinklers had to be removed first.

Some parts of the test specimen are covered from outside with an insulated chamber and sealed through the perimeter. The insulated chamber is then attached to the heating and cooling equipment. Temperature sensors are also installed on the specimen.

Figure 5-15: Thermal Cycling Test setup

5.3.2 Structural performance test setup

The two curtain wall performance tests to check its structural adequacy are the structural (deflection) performance test and the seismic (inter-story drift) movement test. The test is conducted by applying the design wind load for structural performance tests and applying the design displacement for static seismic tests.

Although the tests are done for both serviceability and strength design loads, the test measurements are taken for the serviceability test only. Accordingly, the test setup for a structural performance test is only done to record the measurement data for the serviceability test.

5.3.2.1 Structural Performance (deflection) test setup

5.3.2.1.1 General test setup

For the structural performance test related to the deflection of different components of the curtain wall, such as glass, transoms, and mullion, deflection sensors are used. The sensor installation locations proposed by the test institute are adjusted somehow based on the Finite Element model analysis output where the maximum deflections have occurred. All the deflection sensors used for the test are placed as shown in Figure 5-16 with their corresponding ID.

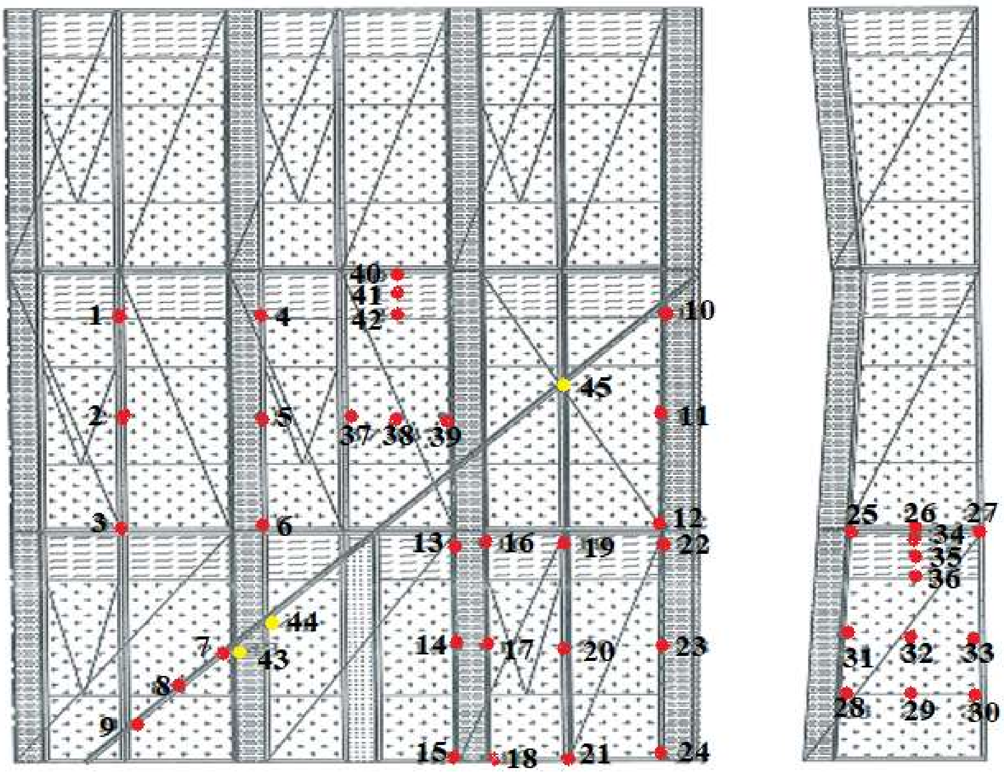


Figure 5-16: Deflection sensors location and ID

The sensors are fixed on the curtain wall surface from inside the chamber. An additional angle iron support is used to put in place and to firmly support the sensors. Three sensors are attached to each element at the bottom, middle, and top parts to incorporate any displacements around the support which have to be deducted from the middle sensor reading to get the actual deflection measurement data.

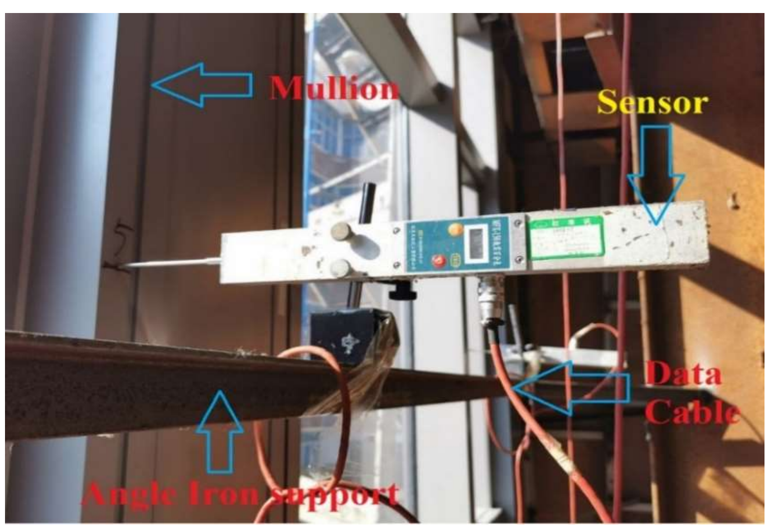


Figure 5-17: Deflection sensor installation

The deflection sensors attached to the mullions are placed vertically at the middle, top, and bottom. The sensor locations concentrate on the 1st and 2nd levels of the façade specimen on both outward and inward sloped mullions.

For locations with the decorative element (fin), two mullions with a spacing of 316mm are used and for a single location, the sensors are placed on both mullions (sensor numbers 13, 14, and 15 on one mullion and 16, 17, and 18 on the other mullion). For the other three locations, the sensors are attached only on one of the mullions (sensor numbers 4, 5, and 6 in one location, 22, 23, and 24 in the second location, and on the third location sensors 10, 11, and 12).

For the locations where there is no decorative element outside, a single mullion is used. The deflection sensors are fixed in two locations of the continuous full span mullions with different slopes (inward and outward). Sensor numbers 1, 2, and 3 are attached on the mullion sloped outward and sensor numbers 19, 20, and 21 on the mullion sloped inward.

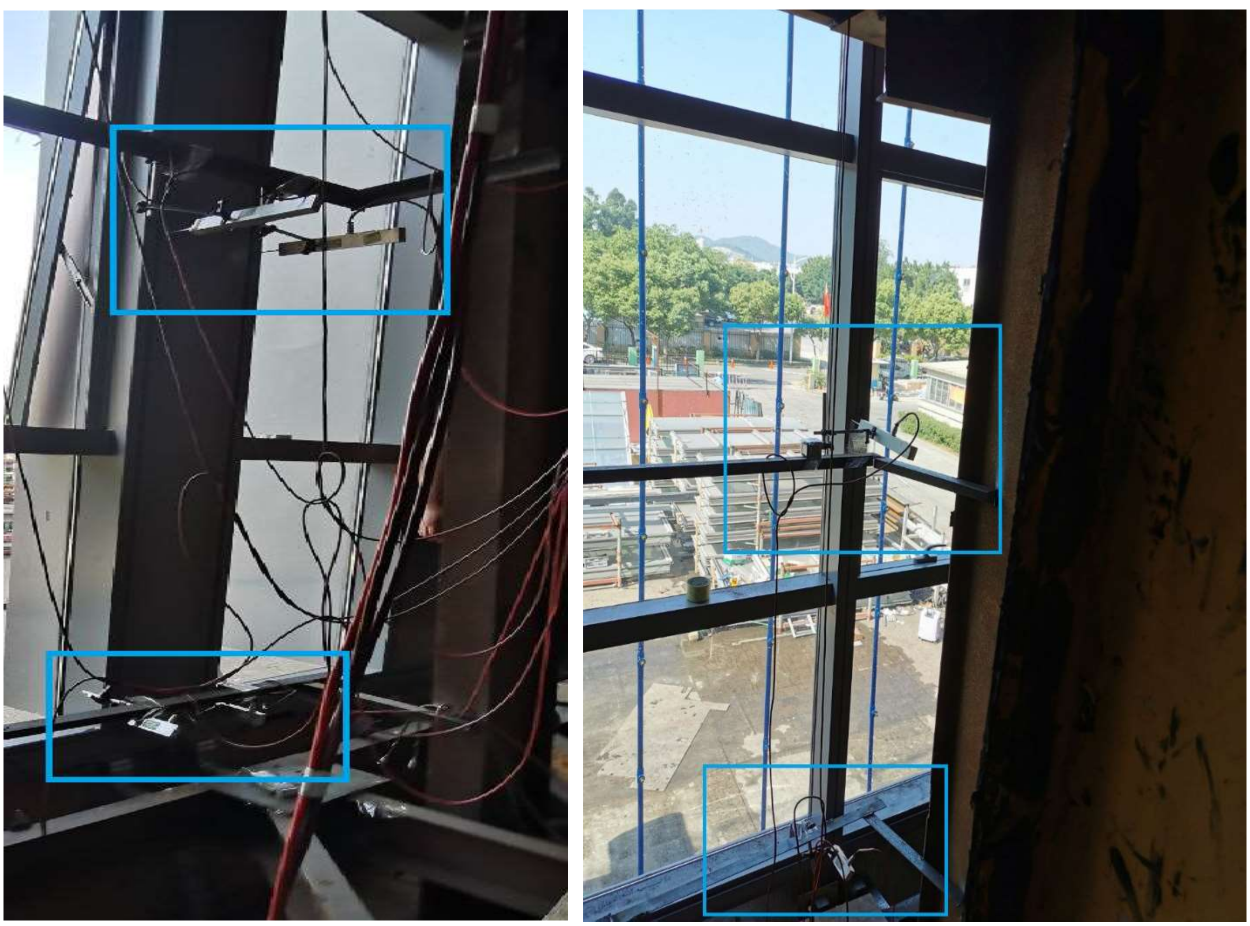


Figure 5-18: Sensors attached on mullion [top, middle, and bottom]

5.3.2.1.2 Thesis specific additional test setup

As part of this thesis paper scope, additional sensors are placed to check the displacement of the joined Aluminum profile mullion members located on the panels along the diagonal breaking line. At these locations, the mullions on a single floor are not a single extruded Aluminum profile rather they are merged in the workshop by joining two profiles using a connector.

To measure the mullion joint displacement of the single mullion at the joint, the sensor number 45 is fixed at the center of the mullion joint.

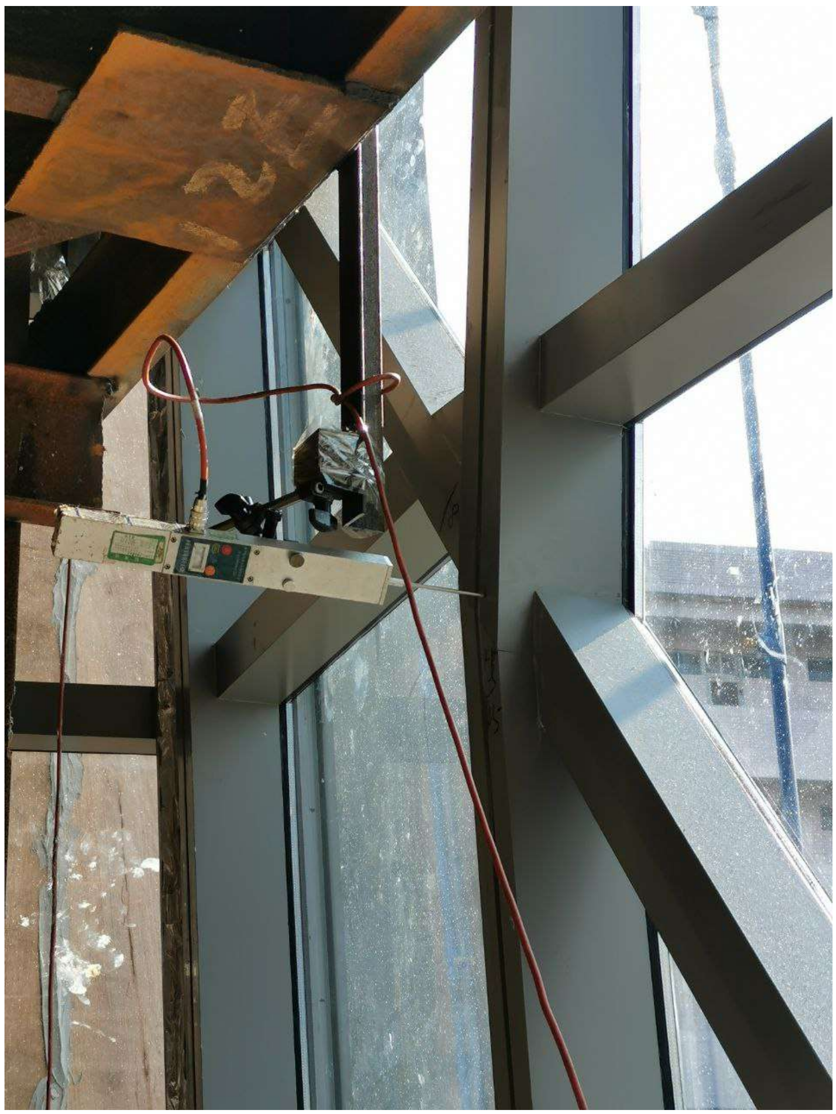


Figure 5-19: Displacement sensors attached to a single joined mullion

For mullions supporting the fin, two sensors (sensor numbers 43 and 44), on the two mullions are fixed to check the displacement. A single sensor is fixed on a single mullion at the joint location to only check the extent of the displacement of the mullion due to the design wind load.

These sensors are only added for the sake of this paper to check whether the joint creates larger displacement which might exceed the deflection limits of Aluminum Profiles which in-turn might transfer stress to the glass and cause glass breakage.

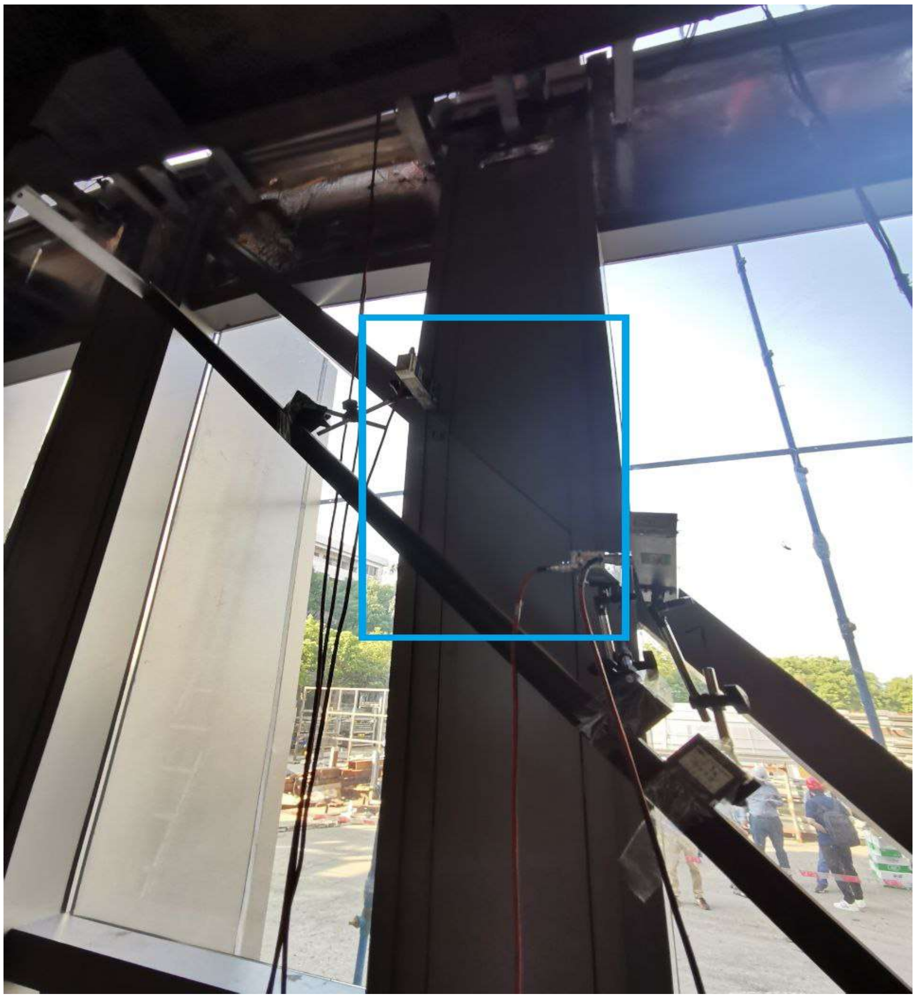


Figure 5-20: Movement sensors attached to joined double mullions

It can easily be noticed that the sensors are only attached at the joint location but not following the same pattern as the remaining sensors (three sensors per element). The reason behind this is the deflection of elements can only be checked for a continuous element but not for joined elements.

5.3.2.2 Seismic movement (inter-story drift) test setup

5.3.2.2.1 General test setup

The general test set up for the horizontal inter-story drift by the static test method is done according to the American standard AAMA 501.4-09. The standard suggests for specimens with multiple stories and the chamber to be constructed to allow the specimens located at the intermediate level including their respective anchorage to move in the horizontal directions.

Due to the requirement for the horizontal load (inter-story drift) test, the middle floor curtain wall panels including the supporting brackets will be pushed left and right with the design /test/ value. To facilitate this, the constructed steel frame supporting the middle floor panels is required to move horizontally while the test load is applied. Accordingly, the middle steel frames are not firmly attached to the rest of the frame but instead additional horizontal steel support is added for the stability of the curtain wall supporting the steel frame during the test.

Figure 5-21: Curtain wall test specimen supporting steel structure

To create the horizontal movement (displacement) of the specimen, two hydraulic jacks are used to push the support steel structure of the panels located at the intermediate level.

Figure 5-22: Hydraulic jack

A sensor is placed at the movable floor element as per the requirement of the standard AAMA 501.4-09 instead of putting them on the test specimen.

Figure 5-23: Displacement sensor

5.4 Performance test

5.4.1 General test overview

The performance test on the curtain wall specimen is done as per the program set by the test institute and agreed upon by all parties. Each test is done following their respective test standards. The following are the tests done on the curtain wall specimen in a sequential order including the standards used:

1. Preloading and Pre-testing (50% of the design wind value) [ASTM E-283]
2. Air Leakage Test [ASTM E-283]
3. Water Penetration Test (Static) [ASTM E-331]
4. Water Penetration Test (Dynamic) [AAMA 501.1]
5. Structural Performance Test at Design Wind Pressure [ASTM E-330]
6. Repeat Air Leakage Test [ASTM E-283]
7. Repeat Water Penetration Test (Static) [ASTM E-331]
8. Seismic Movement Test at design displacement [AAMA 501.4]
9. Repeat Water Penetration Test (Static) [ASTM E-331]
10. Thermal Cycling Test [AAMA 501.5]
11. Repeat Water Penetration Test (Static) [ASTM E-331]
12. Structural Performance Test at 1.5 x Design Wind Pressure [ASTM E-330]
13. Seismic Movement Test at 1.5 x design displacement [AAMA 501.4]
14. Water Penetration Test after cutting the outer sealing tape [ASTM E-331]
15. Controlled dismantle

However, for the sake of this thesis paper, only the structural performance test and the seismic displacement test for serviceability (at design load and displacement) will be discussed.

5.4.2 Structural performance test for serviceability

The structural performance test of the curtain wall specimen is conducted as per the American standard ASTM E330/E330M-14 *Standard Test Method for Structural Performance of Exterior Window, Doors, Skylights, and Curtain Walls by Uniform Static Air Pressure Difference*.

The test specimen is installed on the chamber which has the capability of distributing the static air pressure difference uniformly across the curtain wall specimen. The Air supply and exhaust to and from the chamber is a reverse controllable blower system by using a duct.

As the load-deflection curve is required for the test, Procedure B of the standard ASTM E330 is implemented for the test. According to procedure B, to draw the load-deflection curve, the load must be applied to the specimen in several incremental orders while measuring and recording the corresponding deflections.

The design wind loads (both positive and negative) are divided into 4 equally partitioned load increments are used for the test as per the minimum requirement of the AAMA standard. The following is the test wind load increment proposed for the test including the 50% of the design load being applied as a pre-load.

Table 5-1: Positive wind pressure increment values for the test

No.	**Pressure increment (Pa)**	**Test duration**	**Required Action**	**Remark**
1.	2035 (50% of design load)	10 Sec	-	Pre-load
2.	0	1-5min	Take reading	Record permanent deformation
3.	1017.5 (25%)	10 Sec	Take reading	Record deflection
4.	2035 (50%)	10 Sec	Take reading	Record deflection
5.	3052.5 (75%)	10 Sec	Take reading	Record deflection
6.	4070 (100%)	10 Sec	Take reading	Record deflection
7.	0	1-5min	Take reading	Record permanent deformation

Table 5-2: Negative wind pressure increment for test

No.	Pressure decrement (Pa)	Test duration	Required Action	Remark
1.	-2155 (50% of design load)	10 Sec	-	Pre-load
2.	0	1-5min	Take reading	Record permanent deformation
3.	-1077.5 (25%)	10 Sec	Take reading	Record deflection
4.	-2155 (50%)	10 Sec	Take reading	Record deflection
5.	-3232.5 (75%)	10 Sec	Take reading	Record deflection
6.	-4310 (100%)	10 Sec	Take reading	Record deflection
7.	0	1-5min	Take reading	Record permanent deformation

The test started by applying 50% of the positive design wind pressure by extracting air from the chamber and hold it for 10 seconds and release. After a recovery period of 5minute to stabilize the test specimen from the developed deformation /deflection/, all the deflection measuring gauges are zeroed-out as per the requirement of the standard.

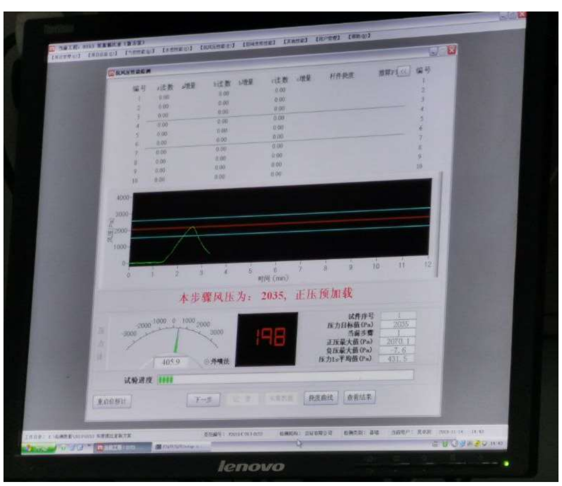


Figure 5-24: 50% of positive wind pressure pre-loading

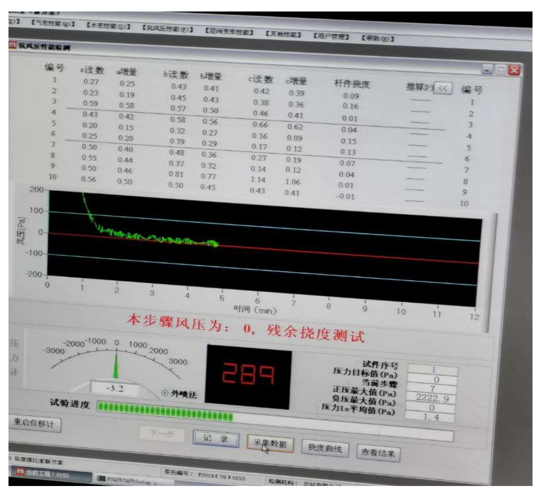


Figure 5-25: 5min. recovery to stabilize the specimen

Once the pre-test is done and all the deflection devices are zeroed-out the actual test with deflection values recording started for the specified increments. The load maintained for 10seconds at the required wind pressure values and deflection readings have been taken before continuing to the next higher incremental value until the maximum positive wind value of 4070Pa (100%) reached.

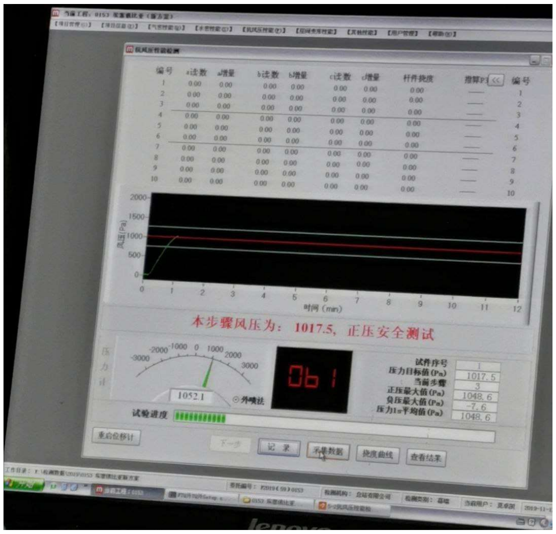


Figure 5-26: 25% of positive wind pressure loading

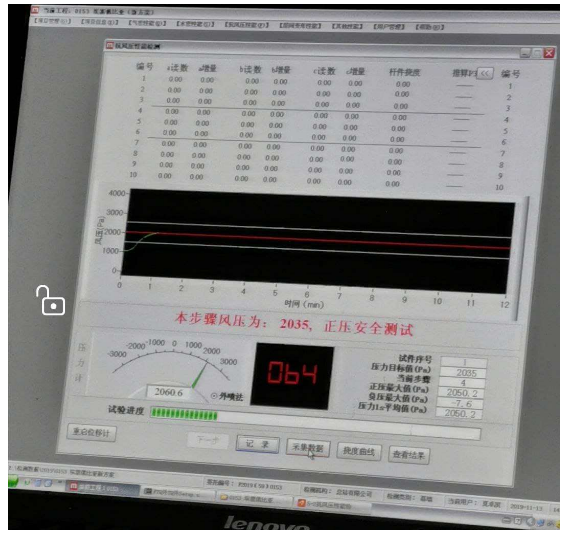


Figure 5-27: 50% of positive wind pressure loading

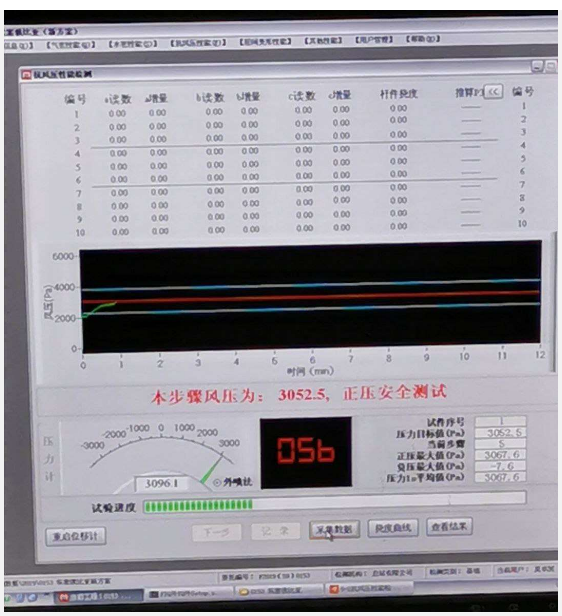


Figure 5-28: 75% of positive wind pressure loading

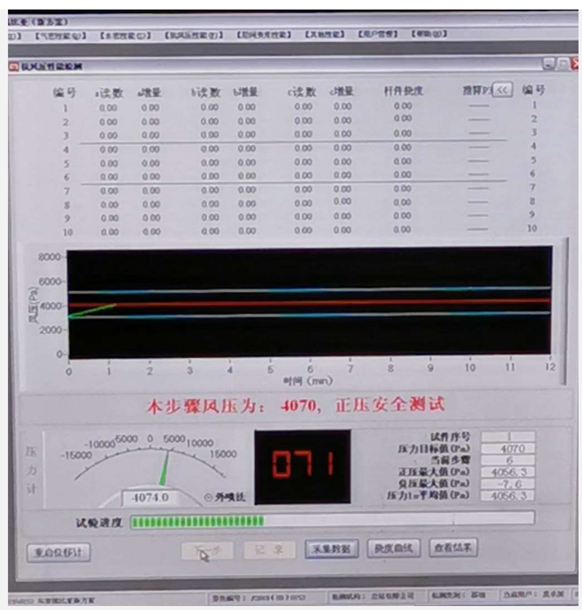


Figure 5-29: 100% of positive wind pressure loading

Finally, the pressure difference is released to zero, and a 5-minute recovery time is given for the specimen to stabilize. Then the deflection readings are taken to record the permanent deformations.

Similarly, for the negative (suction) design wind pressure test the same procedure was applied. To create the suction load on the specimen, the air is supplied to the chamber through the ducts.

After the structural performance test is done, the air infiltration test and water penetration test is also conducted to check any system failure due to the wind pressure loading (after both positive and negative wind pressures).

6 RESULTS DISCUSSION AND COMPARISON

6.1 General Introduction

In this chapter, the results of both the numerical analysis and the full-scale test results are presented. The results of only the subject matters of this thesis paper are presented here and the detailed discussion will follow in the next chapter.

The term “single continuous mullion member” is used for the members spanning full floor height without a joint and supports glass from both sides and doesn’t have decorative fins from outside. And the term “double continuous mullion member” is used for full-floor spanning profiles without a joint that supports on one side the decorative fin and the other side the glazing. When the term continuous is changed to joined (extended) mullion members it refers to the mullion members supporting the diagonal profile and where the two mullion profiles are joined together using a connector to span a full floor height.

6.2 Numerical analysis result

The results of the Finite Element analysis output of the model from the SAP 2000 software are presented hereunder.

6.2.1 Structural analysis output

The structural analysis output results are presented here for the load combinations with 100% of the design wind loads for both pressure and suction loads. The deflection (deformation in this case) in the Y-direction (Uy) is only presented for those mullion members which have been checked through the performance test.

The deflection output Figure of the whole system and the tabulated values of those points of interest for the 100% of both pressure and suction design load are presented below. For the 25%, 50%, and 75% of the design load, the FE analysis output Figures and tables for deflection are presented in Annex A

The nodes with ID 143, 148, and 175 on the SAP model are located at the mullion connection point of the joined mullion members.

The deflection in Y-direction (Uy) value for the 100% of positive design wind pressure is:

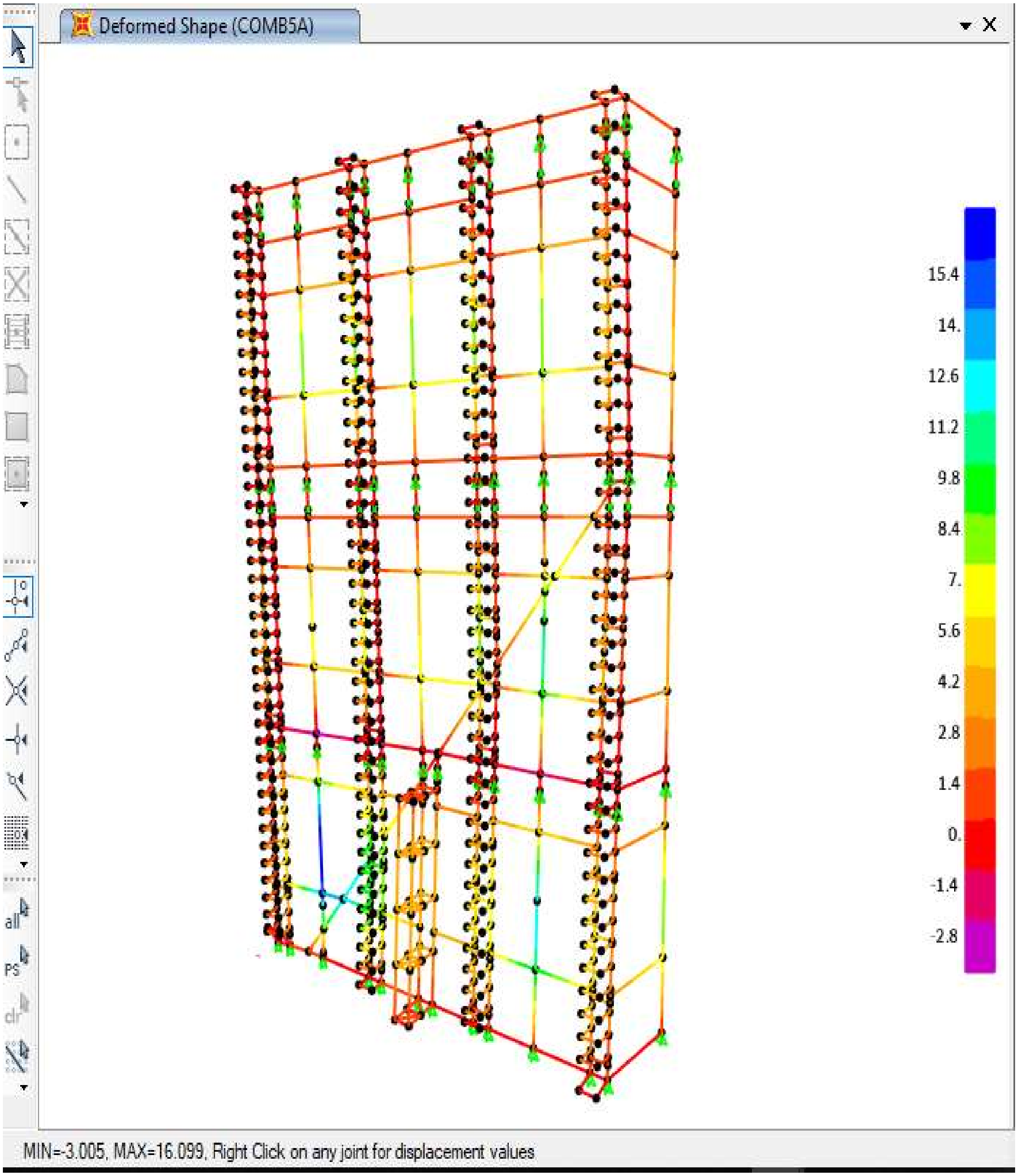


Figure 6-1 Deflection of the frame analysis for 100% of the design positive wind pressure

Table 6-1 Deflection values of the FE analysis for the 100% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID- A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	4070	-3.00	6.53	0.00	8.03	1/2/3	335/399/139
2	4070	-1.45	3.49	0.00	4.21	4/5/6	348/401/307
3	4070	-0.87	3.06	0.00	3.49	10/11/12	334/400/360
4	4070	0.00	4.60	0.00	4.60	13/14/15	311/405/162
5	4070	0.00	6.12	0.00	6.12	16/17/18	317/403/168
6	4070	0.00	11.45	0.00	11.45	19/20/21	308/402/173
7	4070	0.00	5.27	0.00	5.27	22/23/24	319/404/489
8	4070	-	7.13	-	7.13	45	175
9	4070	-	9.31	-	9.31	43	143
10	4070	-	6.93	-	6.93	44	148

Similarly, the deflection values for the 100% of the negative design wind pressure from the FE analysis result are summarized in Table 6-2 and Figure 6-2. The tabulated summary is presented first and the figure from the SAP analysis is shown next.

Table 6-2 Deflection values of the FE analysis for the 100% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID- A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	-4310	3.02	-7.04	0.00	-8.55	1/2/3	335/399/139
2	-4310	1.50	-4.26	0.00	-5.01	4/5/6	348/401/307
3	-4310	0.90	-3.16	0.00	-3.61	10/11/12	334/400/360
4	-4310	0.00	-5.25	0.00	-5.25	13/14/15	311/405/162
5	-4310	0.00	-6.23	0.00	-6.23	16/17/18	317/403/168
6	-4310	0.00	-11.56	0.00	-11.56	19/20/21	308/402/173
7	-4310	0.00	-5.49	0.00	-5.49	22/23/24	319/404/489
8	-4310	-	-7.62	-	-7.62	45	175
9	-4310	-	-10.32	-	-10.32	43	143
10	-4310	-	-7.44	-	-7.44	44	148

The deflection in Y-direction (Uy) value for the 100% of Negative design wind pressure is:

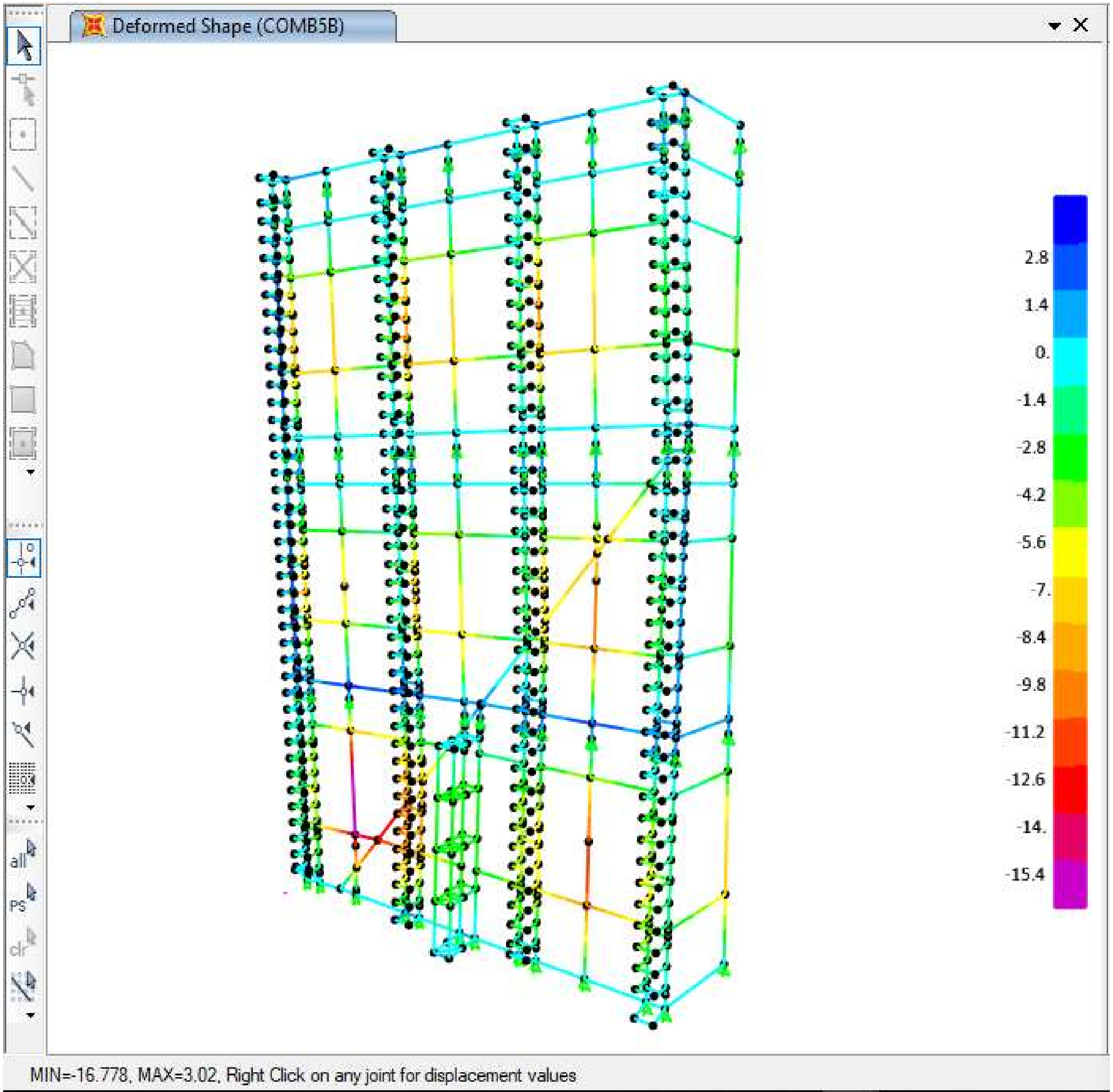


Figure 6-2 Deflection of the frame analysis for 100% of the design negative wind pressure

6.3 Full-height test result

The deflection values of the selected mullion members with sensors attached to them are presented below. The results are only shown in tabulated format and further discussion and comparison with the Finite Element analysis carried out in section 6.4.

The sensor numbers 43, 44, and 45 are added to check the displacement of the members with the jointed mullions. The sensors are placed at the joint location only and no top and bottom sensors are used as in the case of the deflection sensors for the other continuous members.

6.3.1 Structural performance test output

The deflection measurement during testing is done in an incremental approach starting from 25%, 50%, 75%, then 100% of the design wind load for both pressure and suction loads. In this section, only the tabular values of the 100% design pressure and suction wind pressures are presented and the remaining tabular values for 25%, 50%, and 75% of the design wind pressures are presented in Annex B.

The values of the points (A, B, and C) are representing the increment (increased values) instead of the direct displacement readings from the sensors. Points A and C are the bottom and top sensor readings respectively, and B is at the middle.

The member deflection is calculated using the formula:

$$D = B - (A + C)/2 \qquad \text{Eq1}$$

The tabulated deflection values of the 100% design positive wind pressure 4070Pa (which is 4082.3Pa for the test due to difficulty to exactly maintain the test in the specified value) are presented in Table 6-3.

Table 6-3 Deflection values of the test specimen for the 100% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (D)(mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	4082.3	2.58	10.19	6.96	5.42	1/2/3
2	4082.3	4.32	7.84	6.83	2.27	4/5/6
3	4082.3	3.84	6.38	4.59	2.17	10/11/12
4	4082.3	4.39	7.86	3.83	3.75	13/14/15
5	4082.3	4.34	6.84	4.42	2.46	16/17/18
6	4082.3	6.41	15.32	5.27	9.48	19/20/21
7	4082.3	3.62	5.14	2.25	2.21	22/23/24
8	4082.3	-	11.89	-	11.89	45
9	4082.3	-	10.39	-	10.39	43
10	4082.3	-	8.08	-	8.08	44

Similarly, the deflection values for the 100% of the negative design wind pressure -4310Pa (which becomes -4312.7Pa in the test) is presented in Table 6-4

Table 6-4 Deflection values of the test specimen for the 100% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (D) (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	-4312.7	-5.51	-14.51	-5.42	-9.04	1/2/3
2	-4312.7	-3.83	-8.08	-5.78	-3.28	4/5/6
3	-4312.7	-3.69	-8.22	-6.11	-3.32	10/11/12
4	-4312.7	-1.23	-8.99	-8.07	-4.34	13/14/15
5	-4312.7	-2.97	-9.05	-9.71	-2.71	16/17/18
6	-4312.7	-2.40	-15.78	-9.75	-9.71	19/20/21
7	-4312.7	-5.05	-8.78	-7.37	-2.57	22/23/24
8	-4312.7	-	-13.99	-	-13.99	45
9	-4312.7	-	-10.45	-	-10.45	43
10	-4312.7	-	-8.05	-	-8.05	44

6.4 Results comparison and Discussion

The results of the numerical analysis on SAP 2000 and the full height test are presented in section 6.3. In this section, the results of the FE analysis and the test will be discussed and compared in detail.

6.4.1 Structural performance test and numerical analysis results discussion and comparison

The test results of the structural performance test and Finite element analysis for the deflection criteria of the serviceability limit state is checked against the deflection limits set for glazed facades. As part of the discussion for the results of those continuous mullion members spanning full height, checking the deflection against the limit will be done as per the requirements of the standards.

In this section, however, a detailed discussion on the deflection value comparison of the results we get from the FE analysis and the test will be presented. Moreover, it is vital to discuss first the results of the continuous members that span full floor height first, and then a discussion on the joined members will follow.

As per the requirement of the structural test standard ASTM E330/E330M-14 section 4, the purpose (procedure) of the structural performance test is to "observe, measure, and record deflection, deformations, and nature of any distress or failures of the specimen". According to the test institute report, there is no damage or failure seen on the test specimen after the serviceability structural test.

As a basis for the discussion and comparison of the test and the numerical analysis outputs, the deflection values recorded from the test and the SAP 2000 software analysis is used. For quick reference, the figure with the sensors location and ID is presented again here.

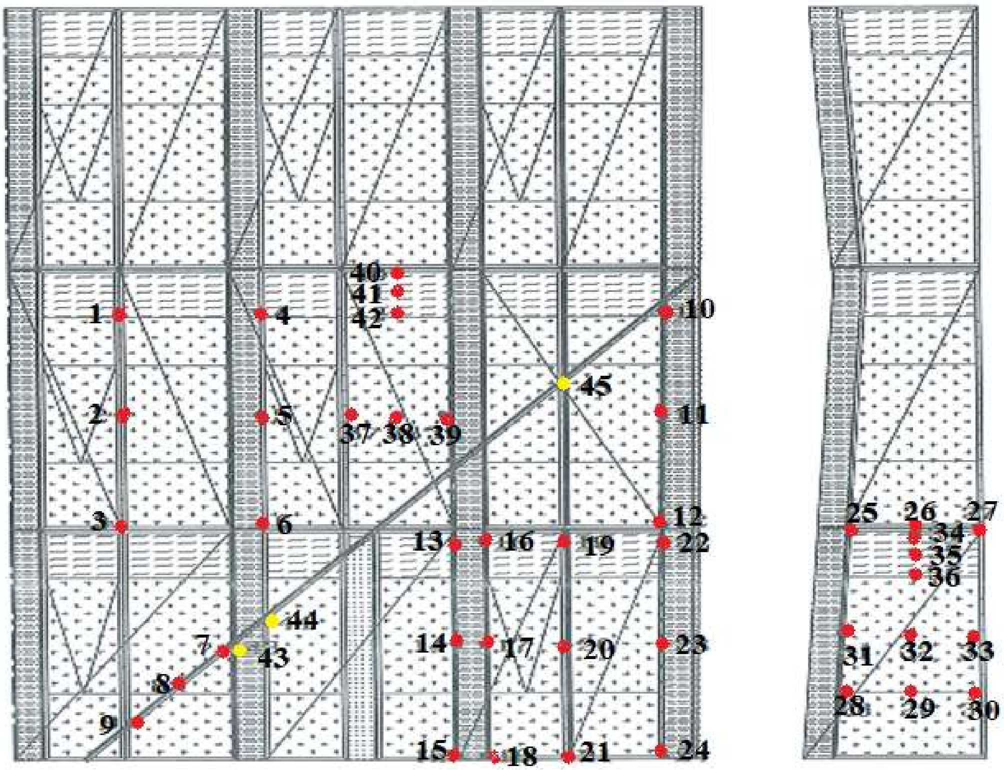


Figure 6-3 Deflection sensors location and ID

According to the requirement of the deflection limit set for the Aluminium members supporting a double glazing, all the member's deflection value is within the requirement. For the unsupported length of the mullion members at the ground level (floor) with the value of L_1=3545mm and that of the second and third level (floor) L_2=3570, the limiting deflection value (D) is:

$$D_1 = (L_1/300) + 5mm = (3545mm/300) + 5mm = 16.82mm$$

$$D_2 = (L_2/300) + 5mm = (3570mm/300) + 5mm = 16.9mm$$

The larger deflections are recorded at the single continuous mullion members as the double members used to support the decorative fins are more rigid and stiffer than the single mullions.

From the two single continuous mullion members where the deflection sensors are installed during the test, the mullion located at the ground level (with sensor numbers 19/20/21) exhibits somehow larger deflections than the mullion located on the 1st floor level (with sensor numbers 1/2/3). This is partly due to the larger horizontally unrestrained member section of size 1900mm of the ground floor panels although the clear span of this floor height is less than that of the 1st floor. This has a clear indication that when the horizontal restraining gap increases, the corresponding vertical member deflection increases.

On the other hand, it can be seen that for the single continuous mullion members, the FE analysis gives a larger deflection value than the test results as shown in Figure 6-4 and Figure 6-5.

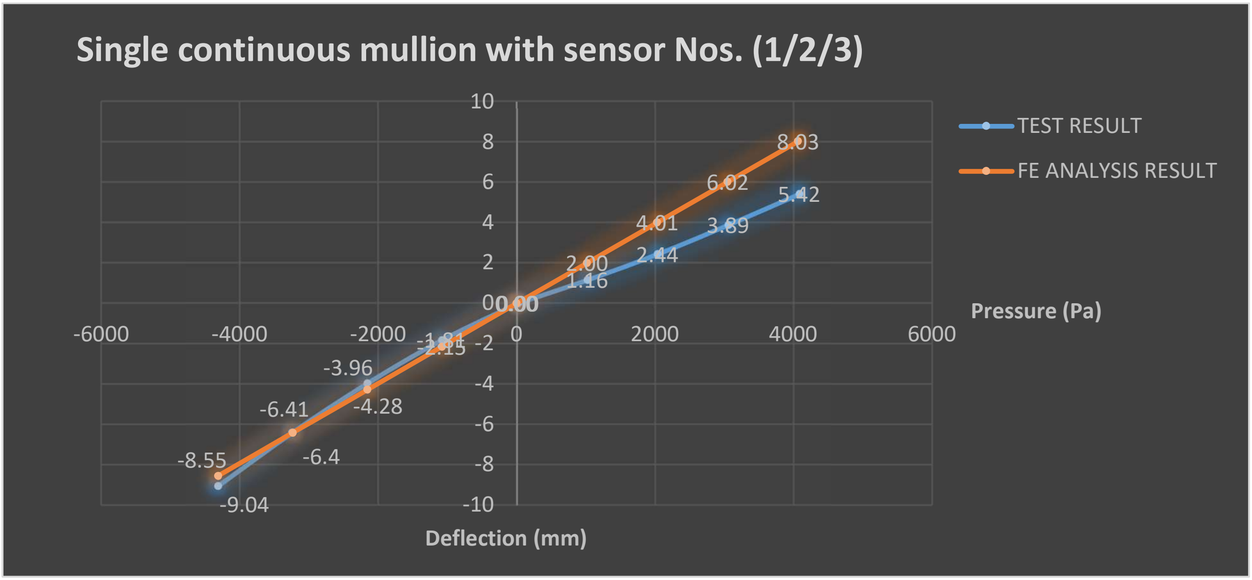


Figure 6-4 Test vs FE analysis deflection results comparison chart for mullion with sensors 1/2/3

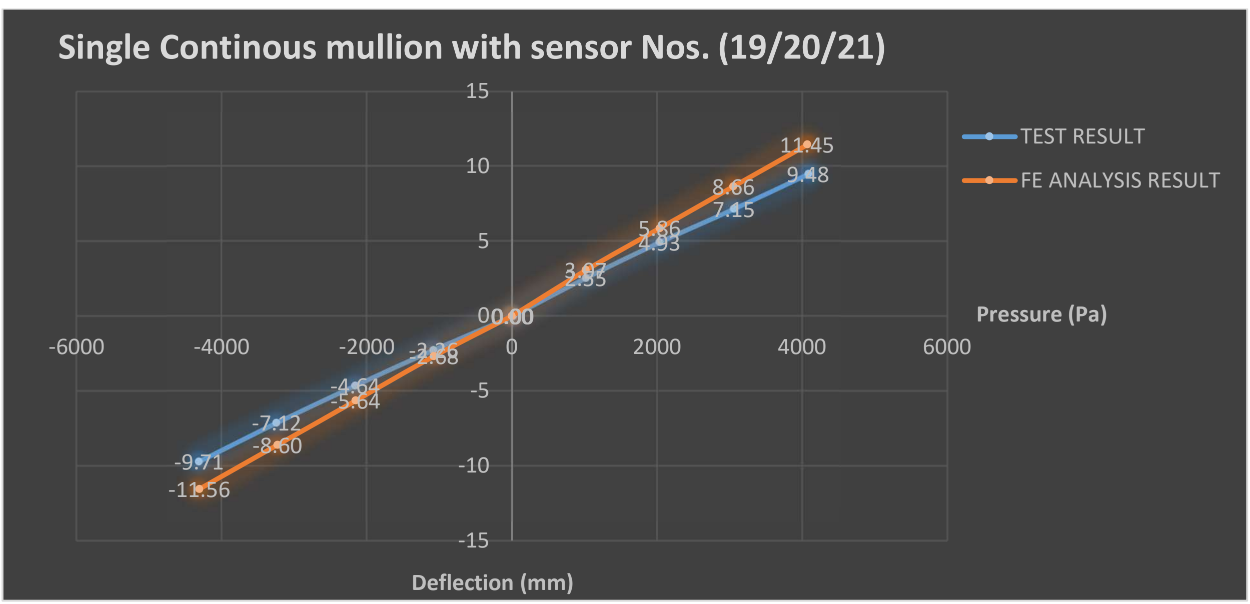


Figure 6-5 Test vs FE analysis deflection results comparison chart for mullion with sensors 19/20/21

The deflection values of the double continuous mullion members are significantly less than that of the single continuous mullions as shown in Figure 6-6. The first reason for such a significant change is the applied wind load on each mullion is from only one side of glazing and the other reason is the two mullions are apart from one another by only a 300mm gap and they are attached using an aluminum connector which makes it rigid.

From Figures 6-8 and Figure 6-9 for mullion members (with attached sensors ID of 13/14/15 and 16/17/18 respectively) it can be seen that the values are different although both mullions are located in the same location supporting a fin. The glazing area supported by each of them is similar but one of the reasons for the difference of the measured values could be the different mullion members used. And the other reason could be for the mullion member (with sensors 13/14/15), the other side of the glazing support is a double mullion that supports the 750mm deep fin which will add for the relatively stiff frame action than the mullion member (with sensors 16/17/18) which is supporting the glazing with a single mullion on the other side.

For the double continuous mullion members also, it can be seen that the FE analysis is giving a larger deflection value than that of the test result in most cases.

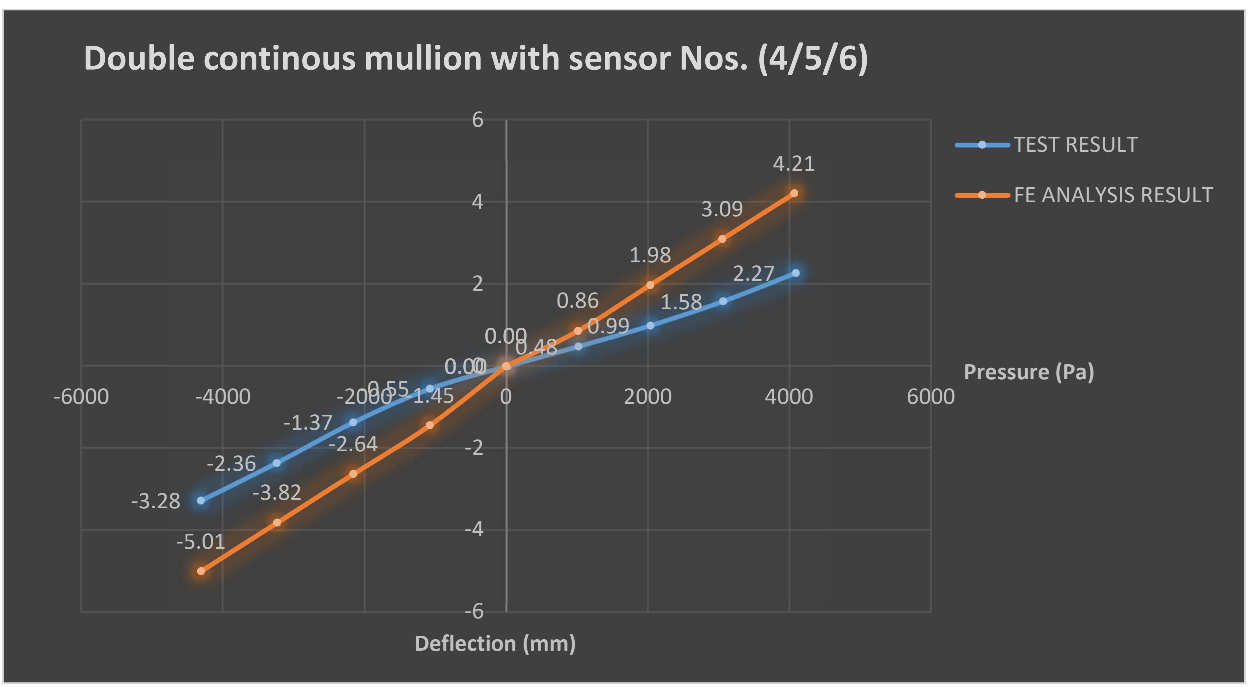


Figure 6-6 Test vs FE analysis deflection results comparison chart for mullion with sensors 4/5/6

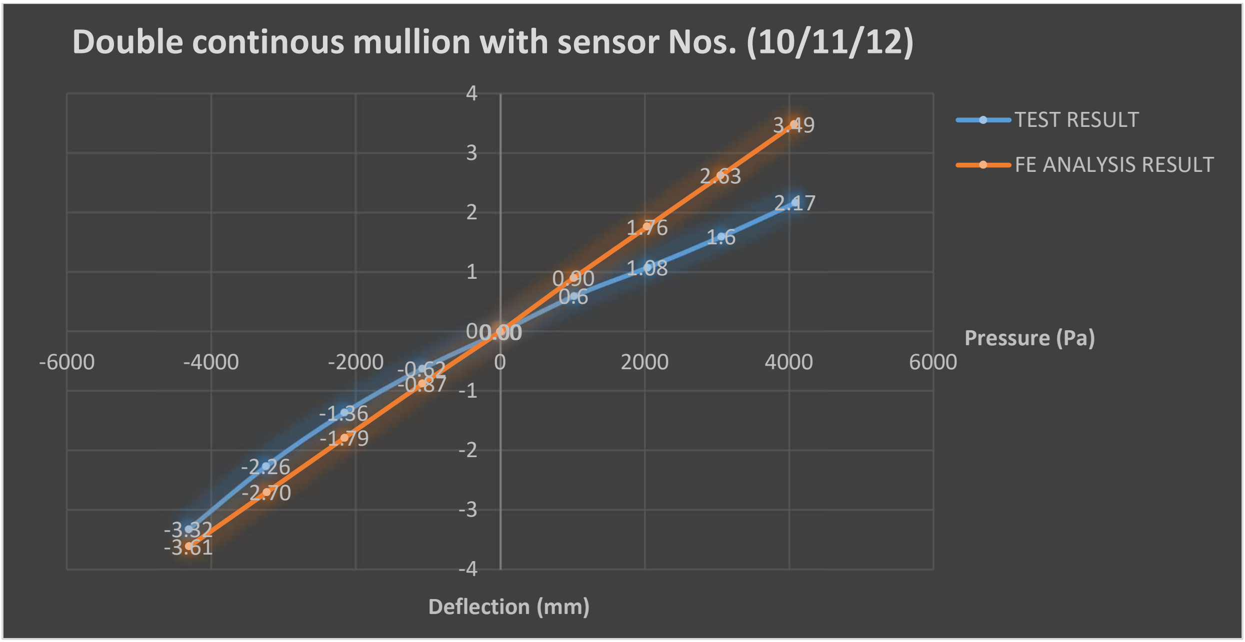


Figure 6-7 Test vs FE analysis deflection results comparison chart for mullion with sensors 10/11/12

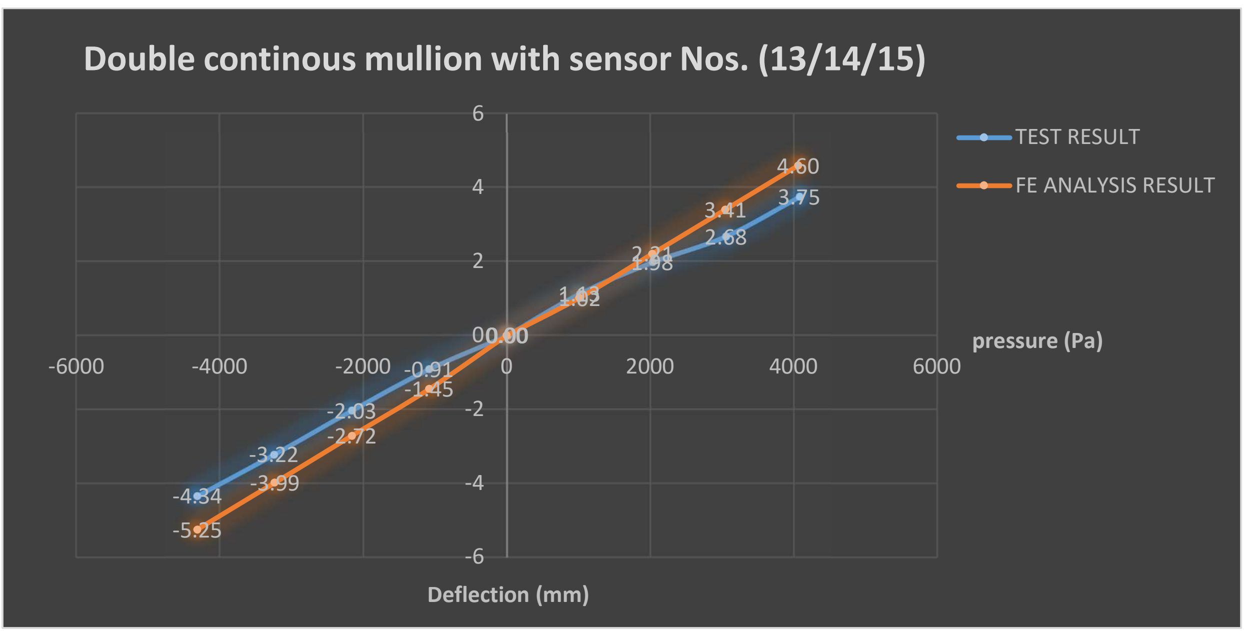


Figure 6-8 Test vs FE analysis deflection results comparison chart for mullion with sensors 13/14/15

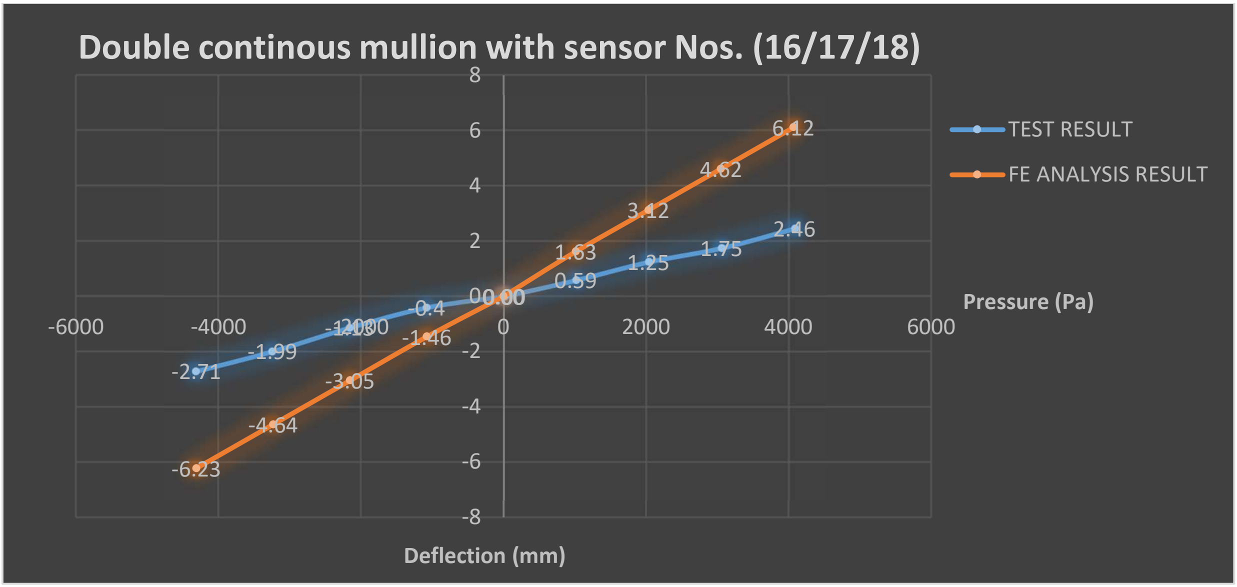


Figure 6-9 Test vs FE analysis deflection results comparison chart for mullion with sensors 16/17/18

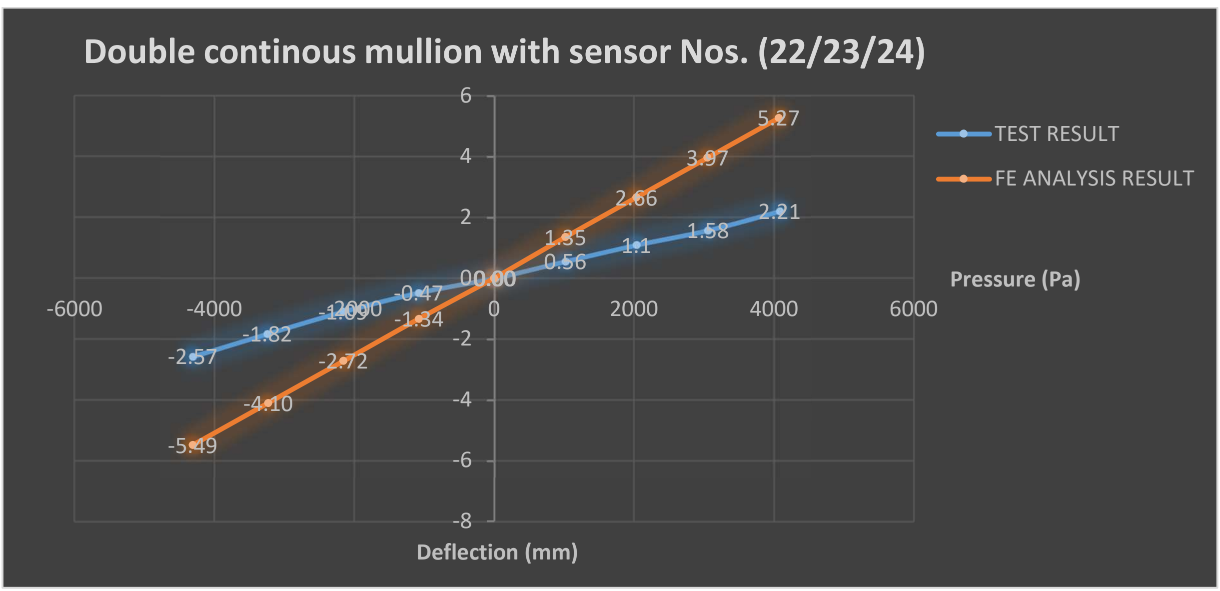


Figure 6-10 Test vs FE analysis deflection results comparison chart for mullion with sensors 22/23/24

In both single and double continuous mullion arrangements the FE analysis value is larger than that of the test result. The FE analysis results shall be on the conservative side than the test result as the Custom-made Aluminum profiles which are used on the test are designed based on those numerical analysis results. This will reassure that the designed Aluminum profiles are on the safe side subject to the proper modeling and design of the numerical analysis model.

However, it is mandatory to understand why the test result is giving lesser values than the FE analysis although the amount of deviations is very minimal and it is expected to have differences between the two results.

While investigating the cause of the lesser deflection results from the test, one critical finding is observed. To better understand these issues the previously presented tabulated deflection values of the 100% positive wind load of both the test and FE analysis are presented in Table 6-3 and Table 6-4.

Table 6-5 Deflection values of the FE analysis for the 100% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	4070	-3.00	6.53	0.00	8.03	1/2/3	335/399/139
2	4070	-1.45	3.49	0.00	4.21	4/5/6	348/401/307
3	4070	-0.87	3.06	0.00	3.49	10/11/12	334/400/360
4	4070	0.00	4.60	0.00	4.60	13/14/15	311/405/162
5	4070	0.00	6.12	0.00	6.12	16/17/18	317/403/168
6	4070	0.00	11.45	0.00	11.45	19/20/21	308/402/173
7	4070	0.00	5.27	0.00	5.27	22/23/24	319/404/489
8	4070	-	7.13	-	7.13	45	175
9	4070	-	9.31	-	9.31	43	143
10	4070	-	6.93	-	6.93	44	148

Table 6-6 Deflection values of the test for the 100% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	4082.3	2.58	10.19	6.96	5.42	1/2/3
2	4082.3	4.32	7.84	6.83	2.27	4/5/6
3	4082.3	3.84	6.38	4.59	2.17	10/11/12
4	4082.3	4.39	7.86	3.83	3.75	13/14/15
5	4082.3	4.34	6.84	4.42	2.46	16/17/18
6	4082.3	6.41	15.32	5.27	9.48	19/20/21
7	4082.3	3.62	5.14	2.25	2.21	22/23/24
8	4082.3	-	11.89	-	11.89	45
9	4082.3	-	10.39	-	10.39	43
10	4082.3	-	8.08	-	8.08	44

From Table 6-5, it can be seen that the FE Analysis result at the supports is zero as it is a pin connection at the dead load support and roller support with restraining in the wind load direction. Whereas on the test result, in table 6-6, both the values at points A and C are all positive numbers and not zero even at the support areas.

And the negative values for numbers 1, 2, and 3 on table 6-5, are recorded at the stack-joint location on the 1st floor, and on table 6-6, all the values are positive similar to the intermediate deflection values at point B.

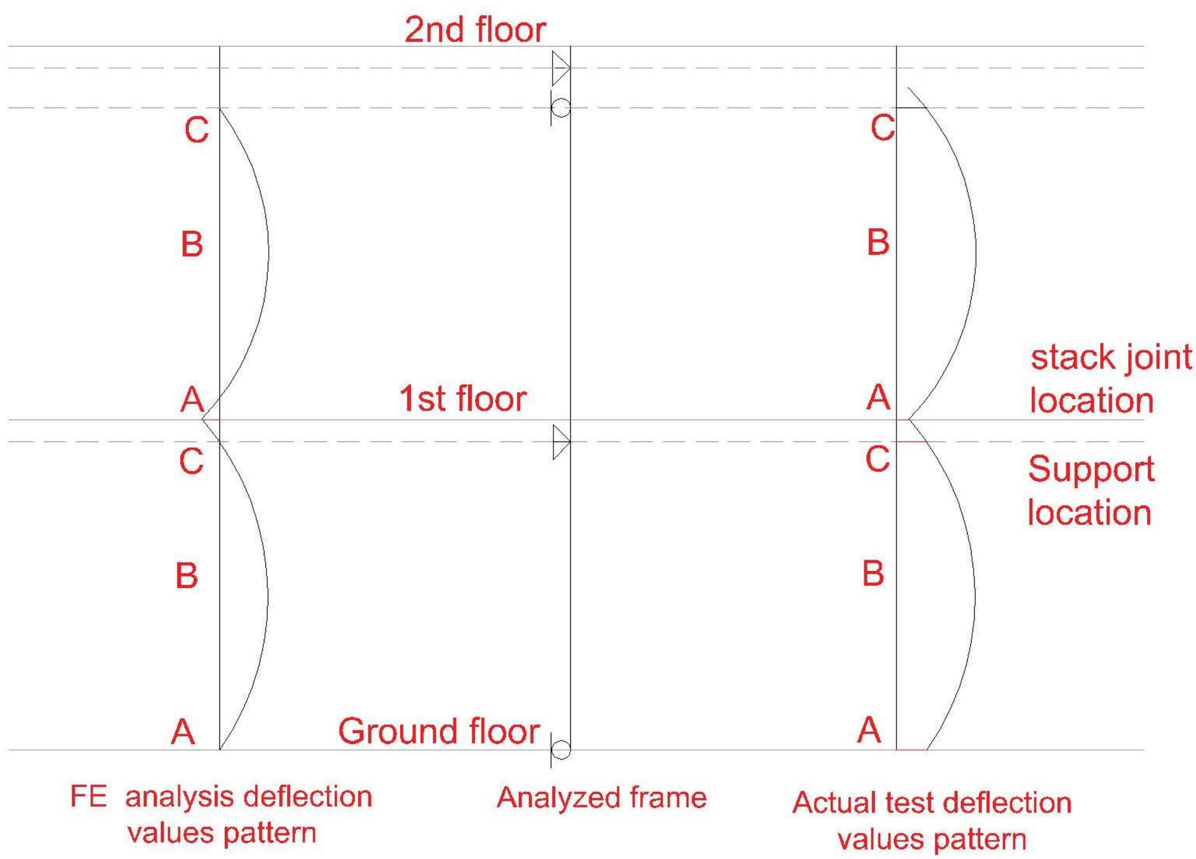


Figure 6-11 Deflection pattern of the FE analysis result and the test result

From Figure 6-11, it can be seen that the displacement readings of the test result is shifted /translated in the Y-direction/ from the ideal location. This is a clear indication that the full panel together with the support displace first before the mullion member starts to deflect. This is in contrast with the Finite element modeling assumptions.

Upon further investigation, it is found that the cause of this panel displacement on the test specimen is related to the gap between the panel supporting hook and the high-strength bolt provided for construction purposes as shown in Figure 6-12.

The presence of this gap forces the vertical adjuster bolt to carry some portion of the applied wind load against its designed purpose of transferring only the dead load of the panel. This might also cause the deflection values of the test to be less than that of the FE analysis result due to some energy loss.

Figure 6-12 Horizontal gaps between the panel supporting hook and the High-strength bolt

Figure 6-13 Additional steel plate inserted on the gap as a modification

Such gaps also cause the specimen to fail several times during the water leakage test until an additional steel plate is stuffed in the gap to monitor this horizontal displacement as shown in Figure 6-13. Unfortunately, there is no deflection data after the modification as the previous test result with all its problems was still within the acceptable limit.

On the other hand, for the joined mullion profile members, the displacement at the joint location only is measured and recorded during the test. The FE analysis result for displacement is also checked at the same joint. The results of both the test and the FE analysis are presented and compared.

At the joined double mullions, the member joint displacement result difference between the test and the FE analysis is not significant although the results of the test are somehow higher than that of the FE analysis result.

However, the results of the adjoined members of the joined mullion (with sensors ID of 43 and 44) are somewhat different although those mullions support the same decorative fin element while they are connected. The logical justifications for such differences are similar as in the case of the continuous mullions.

The joined mullion member (with attached sensor ID no. 43) supports the glazing with a single joined mullion supporting the same glazing on the other side. The relatively larger deflection of the single mullion might contribute to the increase in displacement in this member. Whereas the adjoining Joined mullion member is supporting a relatively smaller size glass than the other member while it shares dead and wind load from the glass on the other side with another double mullion support.

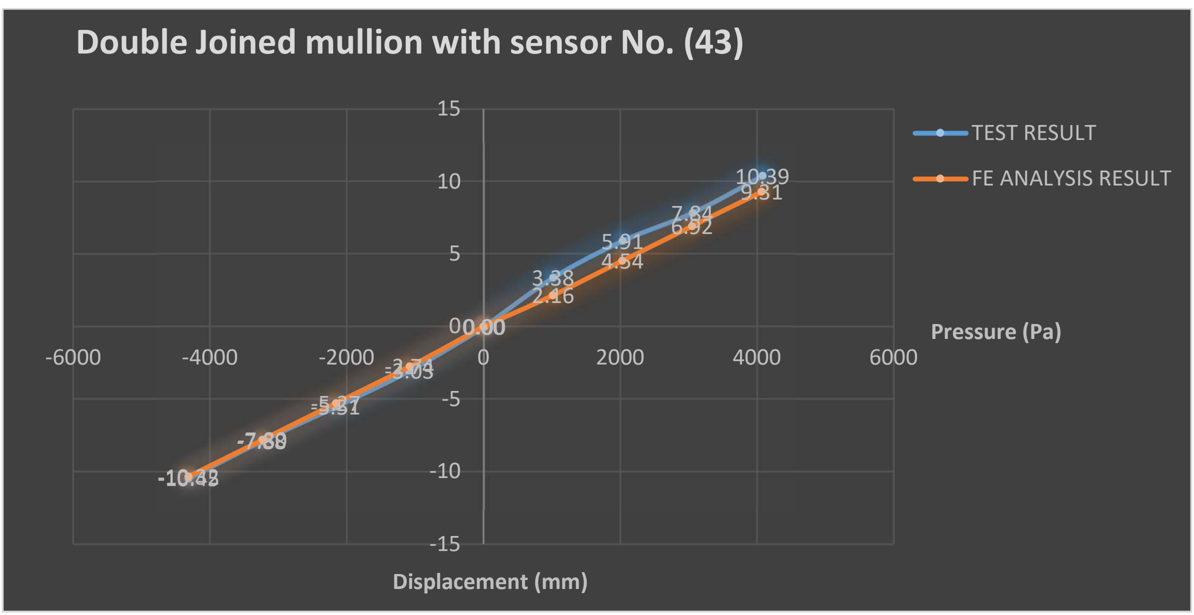


Figure 6-14 Test vs FE analysis deflection results comparison chart for mullion with sensor 43

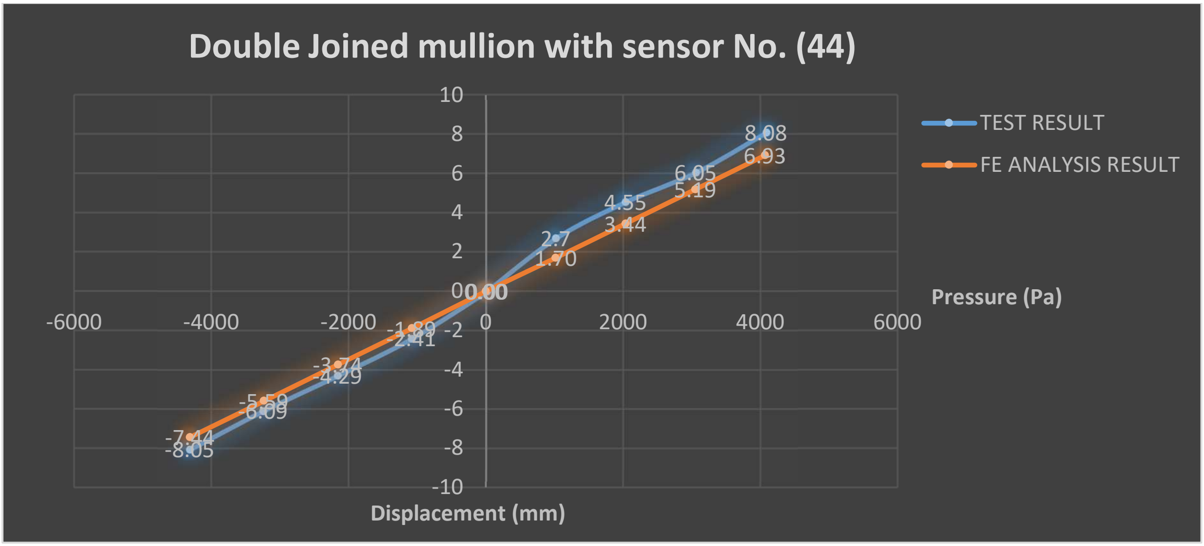


Figure 6-15 Test vs FE analysis deflection results comparison chart for mullion with sensor 44

For the single joined mullion member, the result of the test is significantly greater than that of the FE analysis. The displacement value of the test result at the joint for the negative design load is even close to doubling that of the FE analysis result as shown in Figure 6-16.

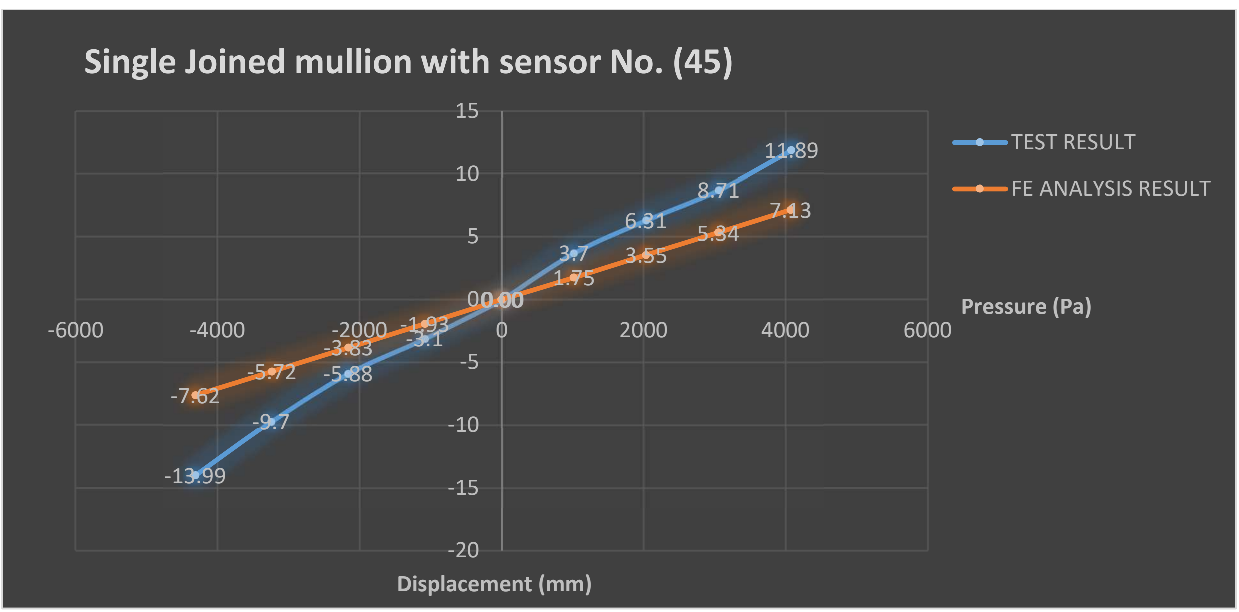


Figure 6-16 Test vs FE analysis deflection results comparison chart for mullion with sensor 45

The displacement data of the joints is only measured around the mid-span of the unit panel while the top and bottom data are not being measured. The higher joint displacement values recorded on the test specimen than the FE model analysis are possibly due to the lack of the top and bottom displacement data which negatively affects the calculation of deflection of the member's test output.

From Table 6-5 of the FE analysis displacement data, it can be seen that the measured values of Point B (at the mid-span) is less than or equal to the calculated member deflection value. This is due to the impact of the measured data at point A (at the bottom) and point C (at the top) has an increasing or maintaining effect on the values of Point B while calculating member deflection. Whereas in Table 6-6 of the test specimen displacement in the Y-direction data, the reverse is true. The measured displacement values of the test specimen at point B is larger than that of the calculated member deflection. Accordingly, the values of the measured displacement at point B from the test is larger than that of the FE analysis output unless the values of the panel translation/displacement/ at the top and bottom support locations in the Y-direction are considered.

Therefore, the larger values of the test result we saw in the graph in Figure 6-16, and also in Figure 6-14 and 6-15 somehow, are the results of the direct use of the displacement data from the sensor at the joint location (located in all the three conditions) around the center of the member without considering the support location displacements.

It can safely be determined that the values of the FE analysis in this specific case might give a larger or closer value with the test if the support conditions were taken into account. That means the FE analysis (as all the members and profiles are designed before the test), predicts well the deflection values of the unitized curtain wall in this specific design and shearing angle.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

As this thesis focuses on both awareness creation of the building façade with special emphasis on unitized curtain wall and also on the numerical analysis, and test result comparison with special focus for the effect of Joined mullion on unit panels, a detailed preview of the curtain walls is presented in Chapter two.

For the rest of the chapters, the Unitized curtain wall modeling and analysis using FE analysis-based software and also a full-scale multiple floor performance test procedure and the deflection results have been presented and discussed in detail.

Accordingly, the following conclusions can be drawn based on the output of the thesis paper:

1. The proposed unitized curtain wall system meets the deflection requirements on both the numerical analysis and on the test results.
2. For continuous members, the numerical analysis gives higher deflection values while for joined mullions it gives lesser values than the test result. This is directly related to the existence of the gap between the curtain wall supporting hook and the high-strength bolt for construction requirements. Due to this gap, the measured data at the support on the test have a negative (deductive) effect on the values at the mid-span while calculating the member deflection. For the joined mullion members as the support values are not taken into account, its displacement value appeared to be higher than that of the FE analysis.
3. The gap between the panel supporting hook and the high-strength bolt for construction tolerance creates a translation (displacement) and possibly some rotations at the support first before the members start to deflect during the test. Such un-restrained displacements at the support (which is restrained in the FE analysis) forces the vertical adjuster bolt to carry a portion of the wind load although it is not designed to carry any lateral load. In addition to that, it has been witnessed that the following water leakage test was continuously failing until this gap is filled with appropriate steel plate material.
4. The member deflection pattern of the numerical analysis and the test results are similar except for the translation and possible rotation of the hook due to the gap for construction tolerance which moves the deflection curve towards the curvature side.

5. In this thesis paper, the effect of the joined mullions is not fully represented because of the presence of the decorative fins and the corresponding placement of dual mullions in a single location where the system largely benefits from the stability and rigidity against the deflection.
6. The numerical analysis model, which is the basis for the Aluminium member design, as in the case of a custom-made unitized curtain wall system, predicts well the member deflection and also displacement results of the joined mullion member for this specific model.
7. Although the numerical analysis predicts the serviceability limit state well, the performance of such complex and irregular facades must be checked by full-scale tests as it is being seen leakages on the test specimen due to construction tolerance gaps at the support.

7.2 Recommendations

Since this Thesis paper is a pioneer for the Structural Engineering stream and also in the country, the presented thesis paper mainly focuses on providing the basic knowledge on the building façade while investigating a specific concern on the unitized curtain wall system. However, the international practice on façade related studies and researches are focused on more of the specific challenges the industry is facing and also focusing on understanding the behavior of materials including the brittle glass infills and the elastic structural load-bearing sealants.

Accordingly, the following recommendations are provided for those who are interested in pursuing other façade related topics and for the stakeholders of the building construction industry:

1. The investigation of the unitized curtain wall with joined mullions is done for the CBE HQ building façade. Based on the analysis results shown in the previous chapters, it is seen that although the test and numerical analysis results for serviceability limit state (deflection) is within the allowable limit for the designed slope of the façade (which is almost 3.5° from vertical), further studies must be conducted to understand the effect of larger slopes and larger span unitized curtain walls on locations with high-wind load and heavy rainfall.
2. The current practice of modelling and analyzing curtain walls, especially unitized curtain walls, by using the FE based software does not fully capture the exact conditions of the

curtain wall. The very difficult aspect of that is modeling the male and female members while providing the gap on the FE based structural analysis software. Therefore, full-scale testing at least for high-rise building facades and any complex facades must be a pre-requisite.

3. Avoid any gap between the panel supporting hook and the supporting brackets for construction tolerance to avoid relative displacements between the hook and the bracket that force the vertical adjuster bolt to carry wind load which leads the bolt to either deflect or disengage. It even leads to the curtain wall to fail by leakage as it is being observed during the water leakage test performed immediately after the structural test.
4. Although it is not in this thesis paper scope to see the effect of using joined and sharp cornered stack joints (male + female transoms) for the seismic and wind-induced inter-story drifts, it is vital to check the movement accommodation and behavior of the unit system at this joint, especially in earthquake susceptible areas.
5. More and more studies and researches related to the current practice of curtain wall construction in Ethiopia can be done within the different disciplines of master's studies like COTM, Architecture, mechanical and structural engineering.
6. The studies on complex and state of the art façade technologies shall be done ahead of time in the country so that we equip the building construction industry with capable designers and supervisors instead of relying on ex-pats when high-rise buildings (in similar or higher scale to the CBE HQ projects) begin to be built in the future.
7. The governing bodies of the building construction must start to emphasize the building façade standard preparations and supervisions as building curtain walls alone covers up to 25% of the building project cost in some cases and as it defines the appearance of the cities.
8. Higher educational institutes shall start giving, at least as a selective course on, the different building facade types, design procedures, material selections, and construction to fill the huge knowledge gap.
9. The use of a Unitized curtain wall for high-rise and medium-rise buildings is now being practiced in the country by mostly foreign companies. Unless the industry starts to be led by local professionals who understand the science and Engineering behind unitized curtain wall or any other facades, the current practice of low quality and wasteful façade construction will continue as it is.

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Annex A: FE Structural analysis deflection output

The Finite element analysis output of the deflection in the Y-direction with 25%, 50%, and 75% of both the pressure and suction design wind loads is presented hereunder but the values for the 100% are shown in section 6.2.1.

The deflection in Y-direction (Uy) value for the 25% of positive design wind pressure is:

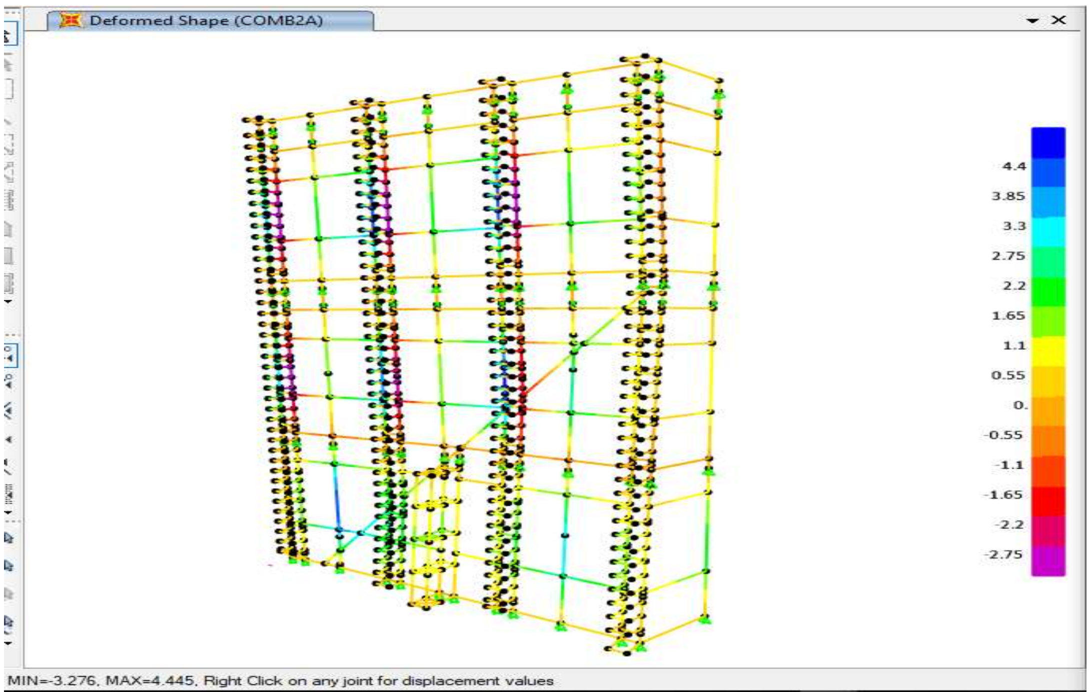

Figure A- 1 Deflection of the frame analysis for 25% of the design positive wind pressure

Table A-0-1 Deflection values of the FE analysis for 25% of the Positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	Remark (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	1017.5	-0.81	1.59	0.00	2.00	1/2/3	139/399/335
2	1017.5	-0.38	0.67	0.00	0.86	4/5/6	307/401/348
3	1017.5	-0.22	0.79	0.00	0.90	10/11/12	360/400/334
4	1017.5	0.00	1.02	0.00	1.02	13/14/15	162/405/311
5	1017.5	0.00	1.63	0.00	1.63	16/17/18	168/403/317
6	1017.5	0.00	3.07	0.00	3.07	19/20/21	173/402/308
7	1017.5	0.00	1.35	0.00	1.35	22/23/24	489/404/319
8	1017.5	-	1.75	-	1.75	45	175
9	1017.5	-	2.16	-	2.16	43	143
10	1017.5	-	1.70	-	1.70	44	148

The deflection in Y-direction (Uy) value for the 25% of Negative design wind pressure is:

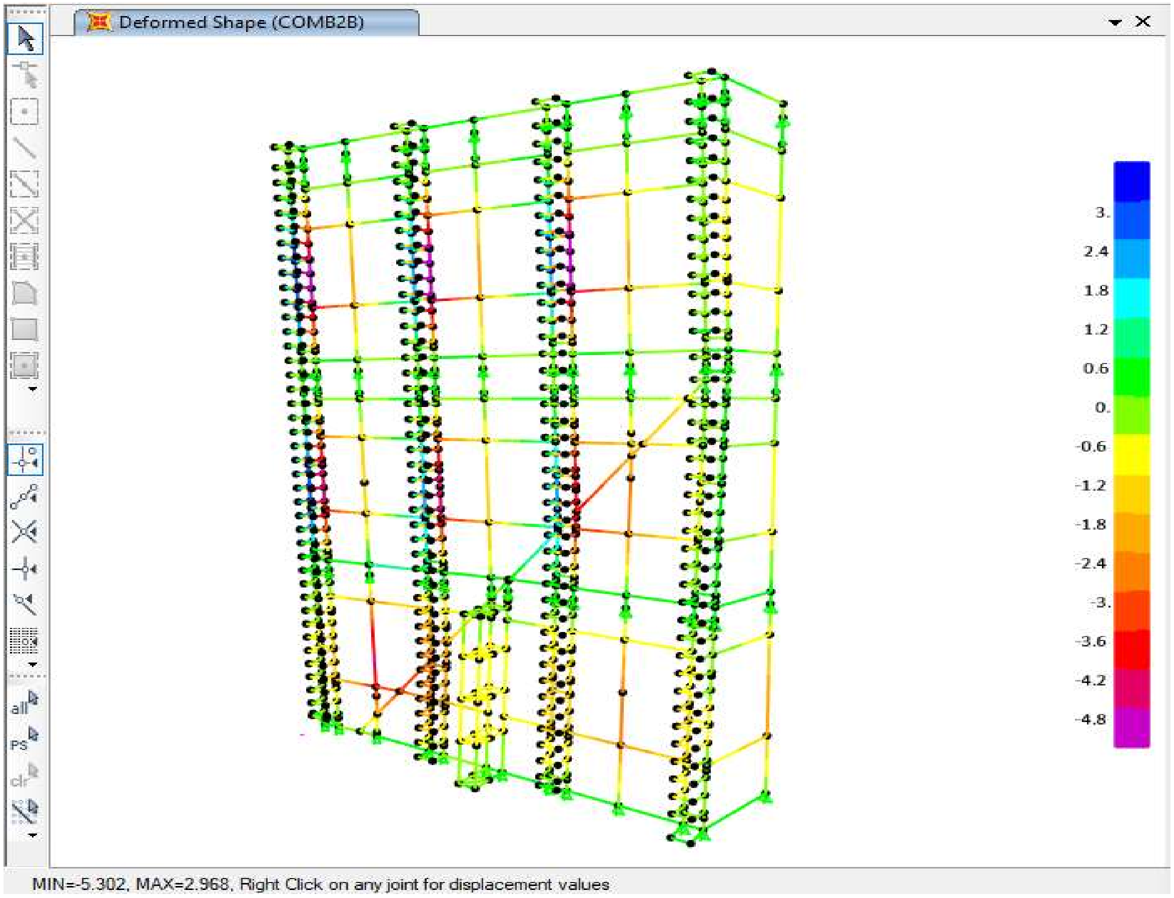

Figure A- 2 Deflection of the frame analysis for 25% of the design negative wind pressure

Table A- 0-2 Deflection values of the FE analysis for the 25% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	-1077.5	0.69	-1.80	0.00	-2.15	1/2/3	335/399/139
2	-1077.5	0.36	-1.27	0.00	-1.45	4/5/6	348/401/307
3	-1077.5	0.22	-0.77	0.00	-0.87	10/11/12	334/400/360
4	-1077.5	0.00	-1.45	0.00	-1.45	13/14/15	311/405/162
5	-1077.5	0.00	-1.46	0.00	-1.46	16/17/18	317/403/168
6	-1077.5	0.00	-2.68	0.00	-2.68	19/20/21	308/402/173
7	-1077.5	0.00	-1.34	0.00	-1.34	22/23/24	319/404/489
8	-1077.5	-	-1.93	-	-1.93	45	175
9	-1077.5	-	-2.74	-	-2.74	43	143
10	-1077.5	-	-1.89	-	-1.89	44	148

The deflection in Y-direction (Uy) value for the 50% of positive design wind pressure is:

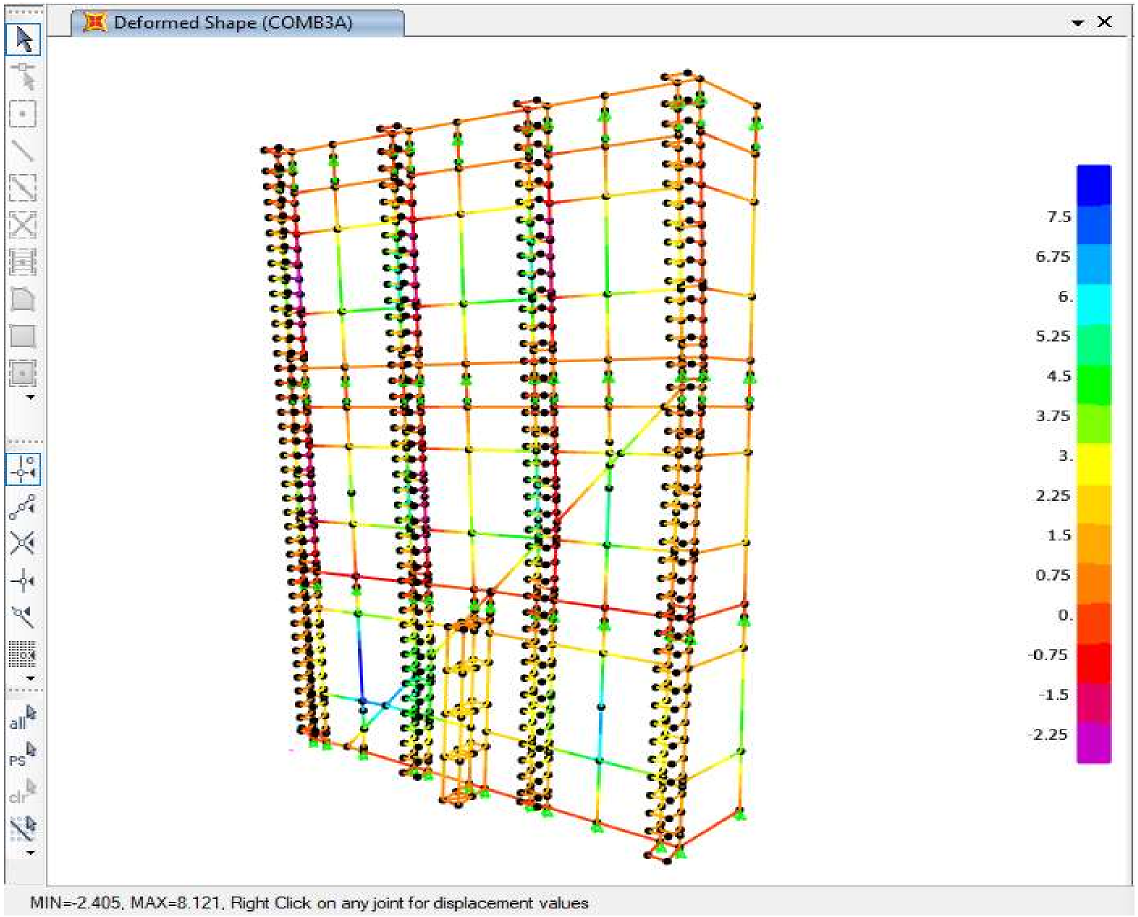

Figure A- 3 Deflection of the frame analysis for 50% of the design positive wind pressure

Table A- 0-3 Deflection values of the FE analysis for the 50% of the Positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	2035	-1.54	3.24	0.00	4.01	1/2/3	335/399/139
2	2035	-0.74	1.61	0.00	1.98	4/5/6	348/401/307
3	2035	-0.44	1.55	0.00	1.76	10/11/12	334/400/360
4	2035	0.00	2.21	0.00	2.21	13/14/15	311/405/162
5	2035	0.00	3.12	0.00	3.12	16/17/18	317/403/168
6	2035	0.00	5.86	0.00	5.86	19/20/21	308/402/173
7	2035	0.00	2.66	0.00	2.66	22/23/24	319/404/489
8	2035	-	3.55	-	3.55	45	175
9	2035	-	4.54	-	4.54	43	143
10	2035	-	3.44	-	3.44	44	148

The deflection in Y-direction (Uy) value for the 50% of Negative design wind pressure is:

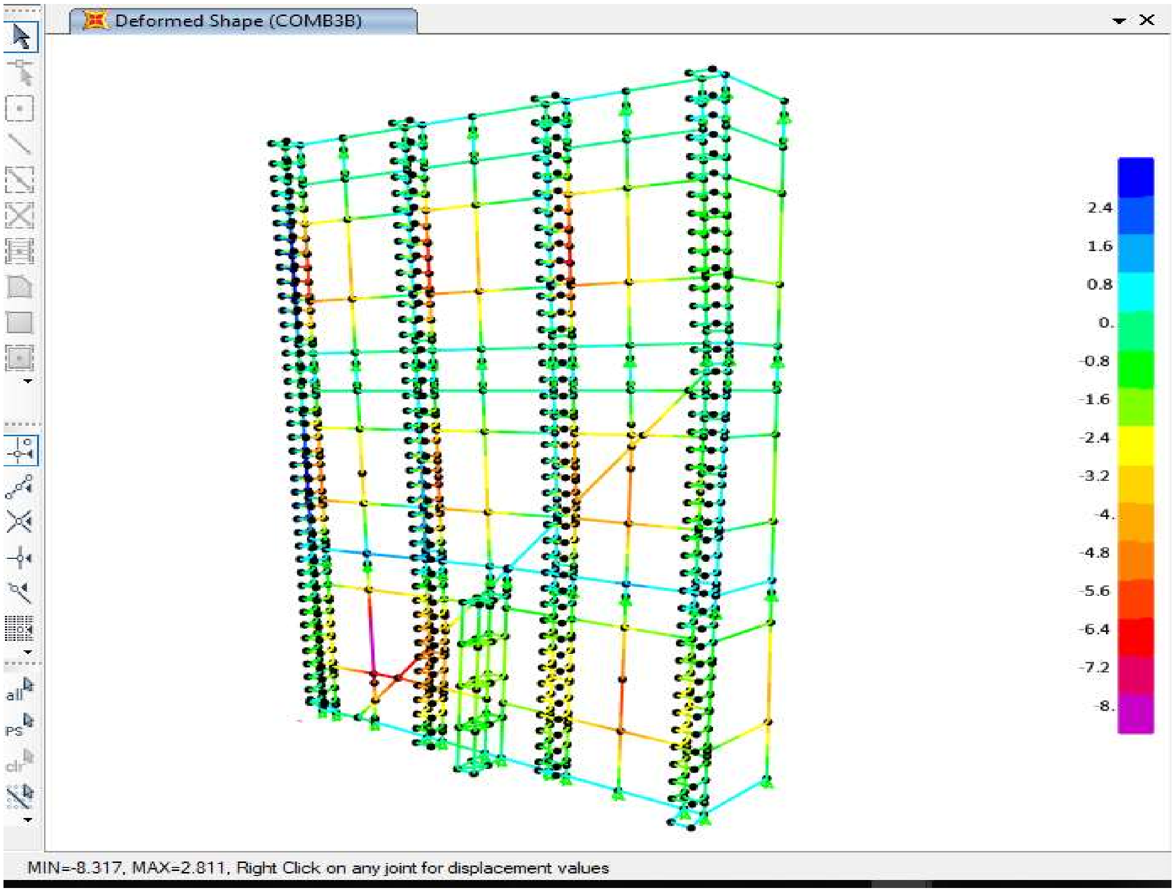

Figure A- 4 Deflection of the frame analysis for 50% of the design negative wind pressure

Table A-0-4 Deflection values of the FE analysis for the 50% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	-2155	1.47	-3.54	0.00	-4.28	1/2/3	335/399/139
2	-2155	0.74	-2.27	0.00	-2.64	4/5/6	348/401/307
3	-2155	0.44	-1.56	0.00	-1.79	10/11/12	334/400/360
4	-2155	0.00	-2.72	0.00	-2.72	13/14/15	311/405/162
5	-2155	0.00	-3.05	0.00	-3.05	16/17/18	317/403/168
6	-2155	0.00	-5.64	0.00	-5.64	19/20/21	308/402/173
7	-2155	0.00	-2.72	0.00	-2.72	22/23/24	319/404/489
8	-2155	-	-3.83	-	-3.83	45	175
9	-2155	-	-5.27	-	-5.27	43	143
10	-2155	-	-3.74	-	-3.74	44	148

The deflection in Y-direction (Uy) value for the 75% of positive design wind pressure is:

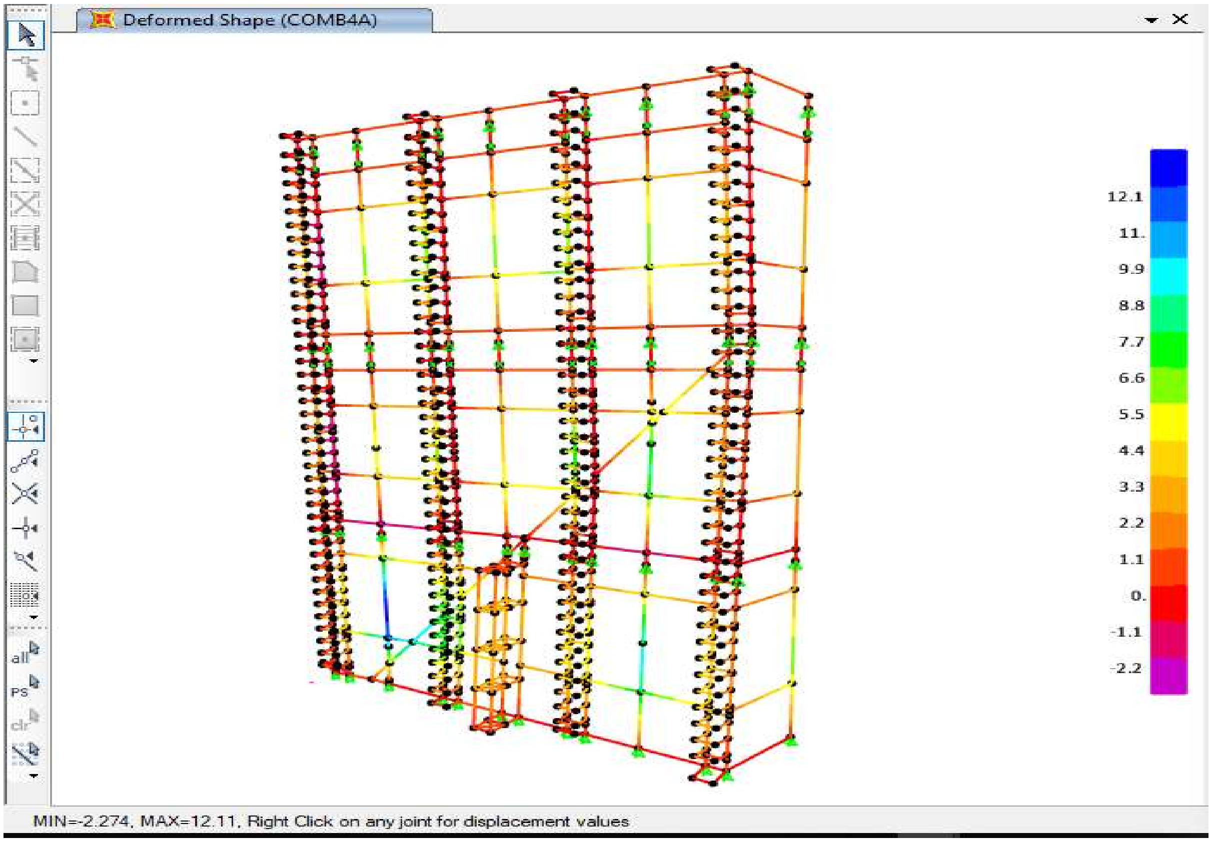

Figure A- 5 Deflection of the frame analysis for 75% of the design positive wind pressure

Table A- 0-5 Deflection values of the FE analysis for the 75% of the Positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	3052.5	-2.27	4.89	0.00	6.02	1/2/3	335/399/139
2	3052.5	-1.09	2.55	0.00	3.09	4/5/6	348/401/307
3	3052.5	-0.65	2.30	0.00	2.63	10/11/12	334/400/360
4	3052.5	0.00	3.41	0.00	3.41	13/14/15	311/405/162
5	3052.5	0.00	4.62	0.00	4.62	16/17/18	317/403/168
6	3052.5	0.00	8.66	0.00	8.66	19/20/21	308/402/173
7	3052.5	0.00	3.97	0.00	3.97	22/23/24	319/404/489
8	3052.5	-	5.34	-	5.34	45	175
9	3052.5	-	6.92	-	6.92	43	143
10	3052.5	-	5.19	-	5.19	44	148

The deflection in Y-direction (Uy) value for the 75% of Negative design wind pressure is:

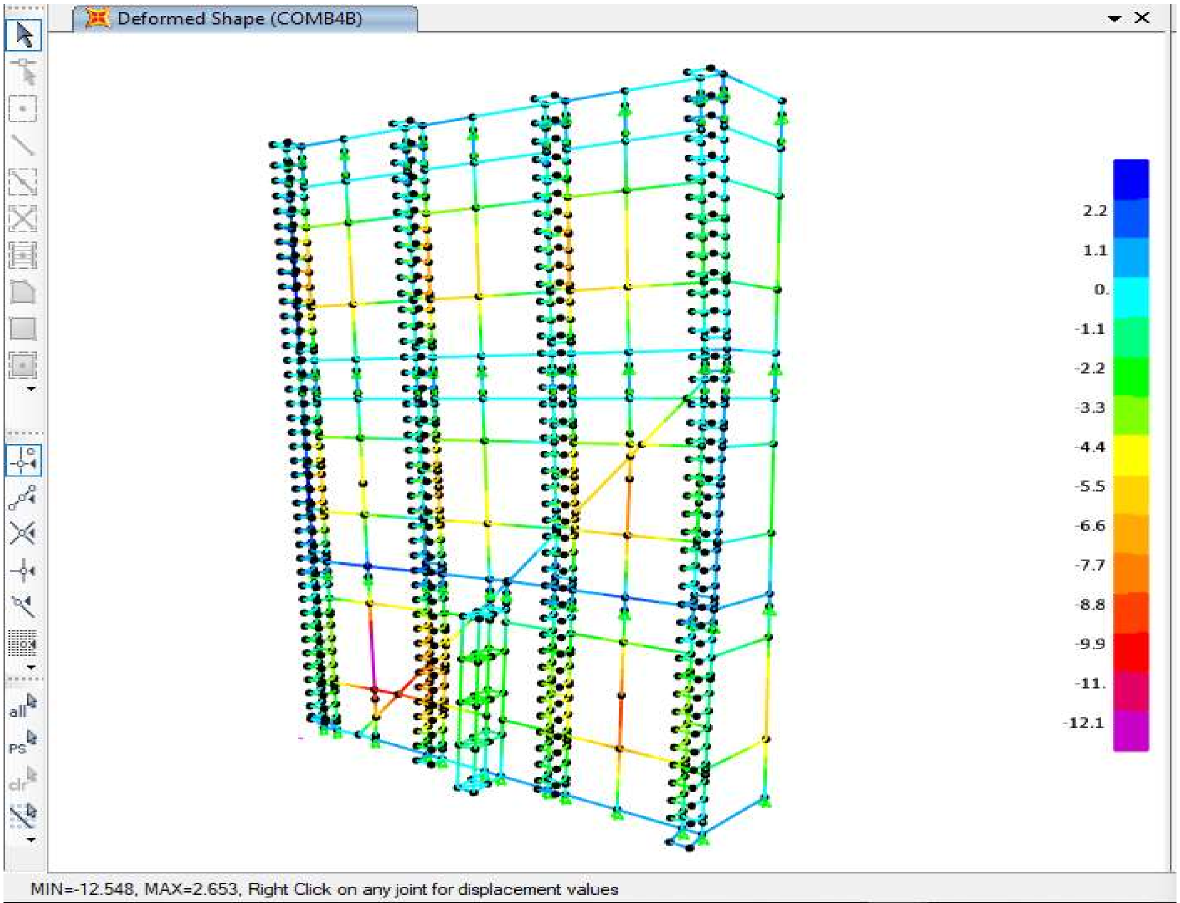

Figure A- 6 Deflection of the frame analysis for 75% of the design negative wind pressure

Table A- 0-6 Deflection values of the FE analysis for the 75% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	TEST (Sensor ID A/B/C)	SAP (Node ID-A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)			
1	-3232.5	2.25	-5.29	0.00	-6.41	1/2/3	335/399/139
2	-3232.5	1.12	-3.26	0.00	-3.82	4/5/6	348/401/307
3	-3232.5	0.67	-2.36	0.00	-2.70	10/11/12	334/400/360
4	-3232.5	0.00	-3.99	0.00	-3.99	13/14/15	311/405/162
5	-3232.5	0.00	-4.64	0.00	-4.64	16/17/18	317/403/168
6	-3232.5	0.00	-8.60	0.00	-8.60	19/20/21	308/402/173
7	-3232.5	0.00	-4.10	0.00	-4.10	22/23/24	319/404/489
8	-3232.5	-	-5.72	-	-5.72	45	175
9	-3232.5	-	-7.80	-	-7.80	43	143
10	-3232.5	-	-5.59	-	-5.59	44	148

Annex B: Full-scale test deflection output

Table B-1 Deflection values of the test specimen for the 25% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	1017.6	1.64	3.70	3.44	1.16	1/2/3
2	1017.6	2.58	3.14	2.74	0.48	4/5/6
3	1017.6	1.36	1.93	1.30	0.6	10/11/12
4	1017.6	1.74	2.55	1.10	1.13	13/14/15
5	1017.6	1.89	2.17	1.27	0.59	16/17/18
6	1017.6	2.72	4.79	1.77	2.55	19/20/21
7	1017.6	0.80	1.21	0.50	0.56	22/23/24
8	1017.6	-	3.70	-	3.70	45
9	1017.6	-	3.38	-	3.38	43
10	1017.6	-	2.70	-	2.70	44

Table B-2 Deflection values of the test specimen for the 50% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	2034	2.00	5.92	4.96	2.44	1/2/3
2	2034	3.26	4.74	4.25	0.99	4/5/6
3	2034	2.05	3.16	2.11	1.08	10/11/12
4	2034	2.79	4.41	2.08	1.98	13/14/15
5	2034	2.72	3.80	2.39	1.25	16/17/18
6	2034	4.12	8.51	3.05	4.93	19/20/21
7	2034	1.37	2.30	1.04	1.1	22/23/24
8	2034	-	6.31	-	6.31	45
9	2034	-	5.91	-	5.91	43
10	2034	-	4.55	-	4.55	44

Table B-3 Deflection values of the test specimen for the 75% of the positive design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	3057.3	2.22	7.96	5.93	3.89	1/2/3
2	3057.3	3.78	6.15	5.37	1.58	4/5/6
3	3057.3	2.64	4.32	2.80	1.6	10/11/12
4	3057.3	3.56	5.89	2.87	2.68	13/14/15
5	3057.3	3.49	5.14	3.29	1.75	16/17/18
6	3057.3	5.18	11.77	4.07	7.15	19/20/21
7	3057.3	1.96	3.33	1.55	1.58	22/23/24
8	3057.3	-	8.71	-	8.71	45
9	3057.3	-	7.84	-	7.84	43
10	3057.3	-	6.05	-	6.05	44

Table B-4 Deflection values of the test specimen for the 25% of the Negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	-1081.5	-1.86	-3.82	-2.17	-1.81	1/2/3
2	-1081.5	-1.62	-2.20	-1.68	-0.55	4/5/6
3	-1081.5	-0.63	-1.49	-1.11	-0.62	10/11/12
4	-1081.5	-0.01	-2.39	-2.96	-0.91	13/14/15
5	-1081.5	-0.67	-2.33	-3.18	-0.4	16/17/18
6	-1081.5	-0.20	-3.87	-3.02	-2.26	19/20/21
7	-1081.5	-0.85	-1.27	-0.75	-0.47	22/23/24
8	-1081.5	-	-3.10	-	-3.10	45
9	-1081.5	-	-3.03	-	-3.03	43
10	-1081.5	-	-2.41	-	-2.41	44

Table B-5 Deflection values of the test specimen for the 50% of the negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	-2159.7	-2.90	-6.99	-3.16	-3.96	1/2/3
2	-2159.7	-2.21	-3.88	-2.81	-1.37	4/5/6
3	-2159.7	-1.34	-3.17	-2.28	-1.36	10/11/12
4	-2159.7	-0.33	-5.02	-5.65	-2.03	13/14/15
5	-2159.7	-1.43	-5.10	-6.52	-1.13	16/17/18
6	-2159.7	-0.74	-8.08	-6.14	-4.64	19/20/21
7	-2159.7	-1.86	-3.33	-2.63	-1.09	22/23/24
8	-2159.7	-	-5.88	-	-5.88	45
9	-2159.7	-	-5.51	-	-5.51	43
10	-2159.7	-	-4.29	-	-4.29	44

Table B-6 Deflection values of the test specimen for the 75% of the Negative design wind pressure

No.	Wind pressure value (Pa)	A	B	C	Member deflection (mm)	(Sensor number A/B/C)
		Y-dir. Disp. (mm)	Y-dir. Disp. (mm)	Y-dir. Disp. (mm)		
1	-3243.8	-4.10	-10.59	-4.28	-6.4	1/2/3
2	-3243.8	-2.99	-5.96	-4.21	-2.36	4/5/6
3	-3243.8	-2.52	-5.85	-4.67	-2.26	10/11/12
4	-3243.8	-0.80	-7.09	-6.95	-3.22	13/14/15
5	-3243.8	-2.30	-7.24	-8.20	-1.99	16/17/18
6	-3243.8	-1.57	-11.94	-8.08	-7.12	19/20/21
7	-3243.8	-4.02	-6.36	-5.07	-1.82	22/23/24
8	-3243.8	-	-9.70	-	-9.70	45
9	-3243.8	-	-7.88	-	-7.88	43
10	-3243.8	-	-6.09	-	-6.09	44