`

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

STUDY ON THE FAÇADE DETAILING FOR WIND LOAD

A Thesis in Structural Engineering

Getachew Melese

July 2020

Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

`

UNDER TAKEN

The undersigned have examined the thesis entitled “Façade Detailing for Wind Load” presented by Getachew Melese a candidate for the degree of Master of Science and hereby certify that it is worthy of acceptance.

Signed by the Examining Committee:

Dr. Shifferaw Taye	____________________	____________________
Advisor	Signature	Date
Dr.-Ing. Adil Zekaria	____________________	____________________
Internal Examiner	Signature	Date
Prof. Dr.-Ing. Grima Zerayohannes	____________________	____________________
External Examiners	Signature	Date
Dr. Mebruk Mohammed	____________________	____________________
Chairman of school	Signature	Date

`

DECLARATION

I certify that the research work titled “Façade Detailing for Wind Load” is created entirely by me. The work has not been submitted to anyone else for review. Wherever material from other sources was used, it was properly acknowledged and referred to.

Signature ____________________ Getachew Melese

`

ACKNOWLEDGMENTS

First and for the most I would like to thank the almightyy of God for his blessings.

Following I am very grateful to my Principal advisor Dr. Shifferaw Taye, for his guidance and encouragement throughout my work. He has always been open-minded and encouraged me to explore potentials and to pursue my interests. His enthusiasm as a teacher is inspiring, and his wise suggestions have always been very helpful. This work would not have been possible without his ceaseless support.

My utmost gratitude goes to my family and my lovely sister who so generously supported me, and encouraged me to focus on this work.

`

ABSTRACT

Building facades are the first aesthetic characteristic that distinguishes one structure from another. Its unique appearance is frequently the subject of trouble attracting. Façade systems are now widely used for new high-rise buildings, and they represent a significant investment in both the building's construction and long-term success. Even the simplest types of façade systems are far more sophisticated than their earlier equivalents, though many of the earliest walls are still performing admirably. More than fifty years of research and development have eliminated the major drawbacks of the original designs, resulting in improved products.

Some people think that a façade system is just an assemblage of glass, aluminum, steel, screws, and sealant. Its construction is not just a combination of various components, but also a sophisticated technology involving complex calculations. Some architects are confused by the relationship between sealant and glass size and wind load, as well as the strength of the glass to withstand the loads. Beginning in the early 1950s, a series of window units and panels joined and supported by simple framing components was a relatively simple but creative concept. Façade system technology has progressed over time to include a wide range of highly engineered designs.

This dissertation will focus on the façade details for wind load using sealant bite for glass, limit state design for glass pane, and finite element analysis methods. Finally, the results were discussed and a conclusion and recommendation on façade details were provided.

`

TABLE OF CONTENT

`

`

LIST OF TABLES

`

LIST OF FIGURES

`

`

CHAPTER ONE

1. INTRODUCTION

1.1. BACK GROUND

Building facades are the first aesthetic characteristic that distinguishes one building from another. They are responsible for its particular appearance and are frequently the subject of heated debate.

The evolution of façades has made them more functional, allowing designers to build high-performance solutions that are also visually appealing, both internally and externally.

Figure1.1 depicts a new commercial building in Hong Kong that received an award for Architectural and Environmental Design. The sensitive handling of variances in floor plate dimensions to suit diverse client requirements, as well as the intelligent use of hi-tech curtain walls and sun-shading devices to provide comfort to users while maximizing the panoramic harbor view (a famous scene in Hong Kong). Without giving in to strong statutory supervision and cutting-edge building technology, the building's overall transparency and architectural expression are maintained.

Figure1.1: One Peking Road at Tsim Sha Tsui, Hong Kong, China (Completed 2003)

`

Major advancements in façade technology give Architects and specialists can now vary the appearance of the building envelope, create an integrated grid system with all of their ideas, such as windows, ventilation elements, aluminum features, etc. while still maintaining a high level of weather proofing.

Façade work includes important building components such as windows, curtain walls, cladding panels, and other elements that form a fundamental part of a building's exterior envelope.

As a result, it is important to ensure that façade structures are appropriately designed, installed, and maintained in order to provide an attractive living environment for the community while also preserving a ‘green' and safe living environment. Figure1.2 depicts a view from one of China's business cities. It demonstrates that today there are many high-rise buildings with a façade envelope.

Figure 1.2: Scene of Hong Kong Island in Hong Kong, China

`

As examples, the following are some project images of Unitized Curtain Wall for high-rise buildings.

Figure 1.3:170m Height, Bank of China, Hong Kong, China (Completed 1991), which was the tallest building in Hong Kong in 20th Century

Figure 1.4: 290m height, International Commerce Centre, Hong Kong, China (Right hand side), which will be the tallest building in Hong Kong.

`

Figure 1. 5: 890m Height, Buji Tower, Dubai

1.2. SCOPE

The façades are subjected to wind, earthquake, dead, alive, temperature, and other loads. The goal of this thesis was to look at the details of a façade in terms of the link between sealant and glass size for wind load.

1.3. STATEMENT OF PROBLEM

Façade systems have become increasingly popular, and they can now be found on a variety of structures. When it comes to determining the details of a façade in terms of the link between sealant and glass size for the wind load, most architects are confused.

`

1.4. OBJECTIVE

1.4.1. General objective

The major goal of this thesis is to investigate the details of the façade for wind loads.

1.4.2. Specific objective

The specific objective of this thesis is:

- To establish a link between structural sealant bite and glass size, as well as to allow for wind pressure.
- To determine the wind resistance of a glass pane.

1.5. OVERALL RESEARCH METHODOLOGY

The study started with a review of previous literature on wind load façade details. Literature papers on façade details can be found in academic journals, unpublished thesis, conference papers, and expert articles. The purpose of this thesis is to demonstrate how to construct facades that can withstand both in-plane and out-of-plane wind loads. As a consequence, the following procedures should be studied in order to accomplish this thesis: structural sealant bite for glazing, limit state design for glass panes, finite element analysis (lisa.8), and case study.

`

CHAPTER TWO

2. LITERATURE REVIEW

2.1. INTRODUCTION

This chapter will go through some of the research that has been done on the behavior of the façade system. The facade is defined by its functional relationship to the structure of the building. It describes a building's enclosure as being separate from and attached to the building's skeletal system. The facades are the most abused building elements, being subject to wind loads, extreme events, building movements, rapid temperature changes, driven rain, air pollution, and corrosion (Jose S. 2013).

Nowadays, a facade system represents a significant investment in the building's construction as well as its long-term profitability. A facade system is not just a barrier to a building's external envelope; it's also critical to its image and perception. A good curtain wall design system with high performance is required; otherwise, future maintenance costs would be high.

2.2. FAÇADE SYSTEM

Based on the material utilized, the façade system can be classified into several types, including:

- Metal (aluminum, stainless steel),
- Timber (treated),
- Masonry façade (brick and terracotta) and
- Glass and natural stone (glass, sandstone and limestone (Gerd H, 2017).

Glass façade systems (GFS) have grown in popularity in recent times and may now be found in a wide range of commercial, industrial, institutional, and residential buildings. The glass façade system has a significant impact on the physical appearance of the building and serves as a barrier between the interior and exterior surroundings.

Furthermore, the development of structural glass with larger dimensions has allowed architects and façade engineers to construct load-bearing structural glass façade systems.

2.2.1. GLASS

Glass is a brittle material and it fails in a sudden and catastrophic manner. Glass is weak in tension due to the nature of its atomic structure and then susceptibility to flaws and not resist crack propagation. When glass is loaded in tension it behaves purely elastically until it fails suddenly at the ultimate tensile strength, but structural ductile materials like; steels, aluminum alloys and even reinforced concrete that can accommodate plastic deformation after yield point as in Figure 2.1 below. Highly stressed areas results in a higher probability of failure (DB.HK, 2018).

At the minimum level of stress, most of the materials obey Hooke’s law means that the strain is linearly proportional to stress. Ductile materials like; metals and plastics have a significant portion of plastic deformation after they have been reached their yield point, whereas brittle materials like glasses and ceramics can accommodate very little plastic deformation and then fail suddenly.

At normal temperature glass does not undergo creep or “flow” and fatigue in the metallurgical sense. However; in the glass there is slow growth of micro-cracks under sustained or cyclical loads. Once the cracks have been reached a critical size then the glass may be fail suddenly in a brittle manner.

`

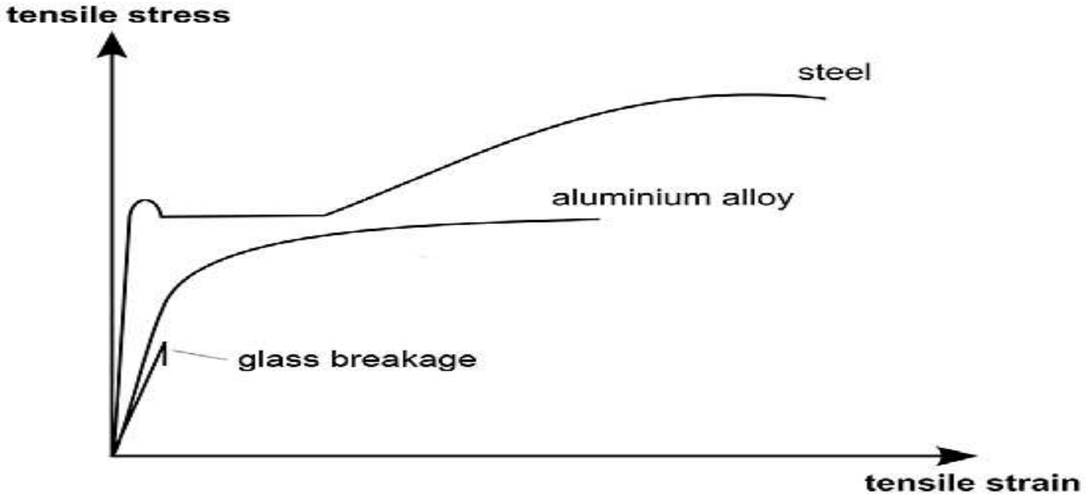


Figure2.1:Stress-strain behaviors of glass, steel and aluminum alloy (source Naimeh. K, 2004)

The typical composition and physical properties of soda lime silicate glass are shown in tables 2.1 and 2.2 respectively.

Table 2.1 Typical composition of soda lime silicate glass (source Naimeh K, 2004)

Chemical Name	**Chemical Formula**	**Weight Percentage**
Silica	SiO_2	69% - 74%
Lime	CaO	5% - 14%
Soda	Na_2O	10% - 16%
with small amounts of magnesium, aluminum, iron and other elements		

Table 2.2 Typical physical properties of glass (source Naimeh K, 2004)

Property	**Symbol**	**Value**
Modulus of elasticity	E	70,000 N/mm^2
Shear modulus	G	$E / [2(1 + \nu)]$
Poisson's ratio	υ	0.22
Coefficient of thermal	α	9 × 10-6 /°C
Density	ρ	2,650 kg/m3

The most common types of glass available in construction of façades are Annealed glass, heat-strengthened glass, toughened glass or fully tempered glass and according to its assembling also can be laminated glass and insulating glass (Tom castle, 2012).

`

a. Annealed Glass

Annealed glass, also known as float glass, has been cooled gradually from a high temperature during manufacture to reduce residual stress and then cut by scoring and snapping. Annealed glass is the most common, weakest, and most usually breaks into huge fragments before forming sharp-edged, pointed shards, as depicted in figure 2.2 below.

The flaws in the glass may be created from the cutting, grinding or drilling of the glass and from the environment to which the glass has been subjected (e.g. humidity promotes crack growth).

Figure 2.2: Crack propagation in annealed glass (source Tom castle, 2012)

b. Heat-Strengthened Glass

Heat-strengthened glass has undergoes a controlled heating and cooling process to improve the resistance to mechanical and thermal stresses. In this process, creates a permanent compressive surface stress and a permanent tensile internal stress are simultaneously induced in the glass (Tom castle, 2012). The compressive surface stresses of heat strengthen glass gives the glass a bending strength higher than that of annealed glass and decrease the failure of glass since the surface pre stress has to be overcome before a bending failure can occur. The residual strength

`

is lower and breaks into larger fragments. The residual compressive surface stress of the heat-strengthen glass is in the range 24–69 N/mm^2 (BDHK, 2018).

The benefit of the heat strengthening process is the surface cracks do not easily propagate as the heat strengthened glass is under compressive stress.

Figure 2.3: Crack pattern of heat strengthened glass (source Tom castle, 2012)

c. Toughened Glass or Fully Tempered Glass

Tempered glass, also known as "fully tempered" or "thermally toughened" glass, is made in the same way as heat-strengthened glass but is quenched (cooled) faster, resulting in a beneficial residual stress field with tension on the interior and compression on the surface. The compressive surface stress of toughened glass is higher in magnitude than heat-strengthened glass. So, toughened glass gives a higher bending strength than heat-strengthened glass. The high strength of the glass means it is far less likely to fail than either annealed or heat strengthened glass types when subjected to mechanical or thermal stresses. The residual compressive surface stress of toughened glass is over 69 N/mm^2 (Tom castle, 2011). This heat treatment results in a larger variation between the compressive stress at the surface and tensile stresses at the interior, as shown in Figure 2.4. This type gals has the highest structural capacity, its residual strength is lowest and breaks into small fragments, which do not have sharp edges and are unlikely to cause deep cutting injuries (Figure 2.5).

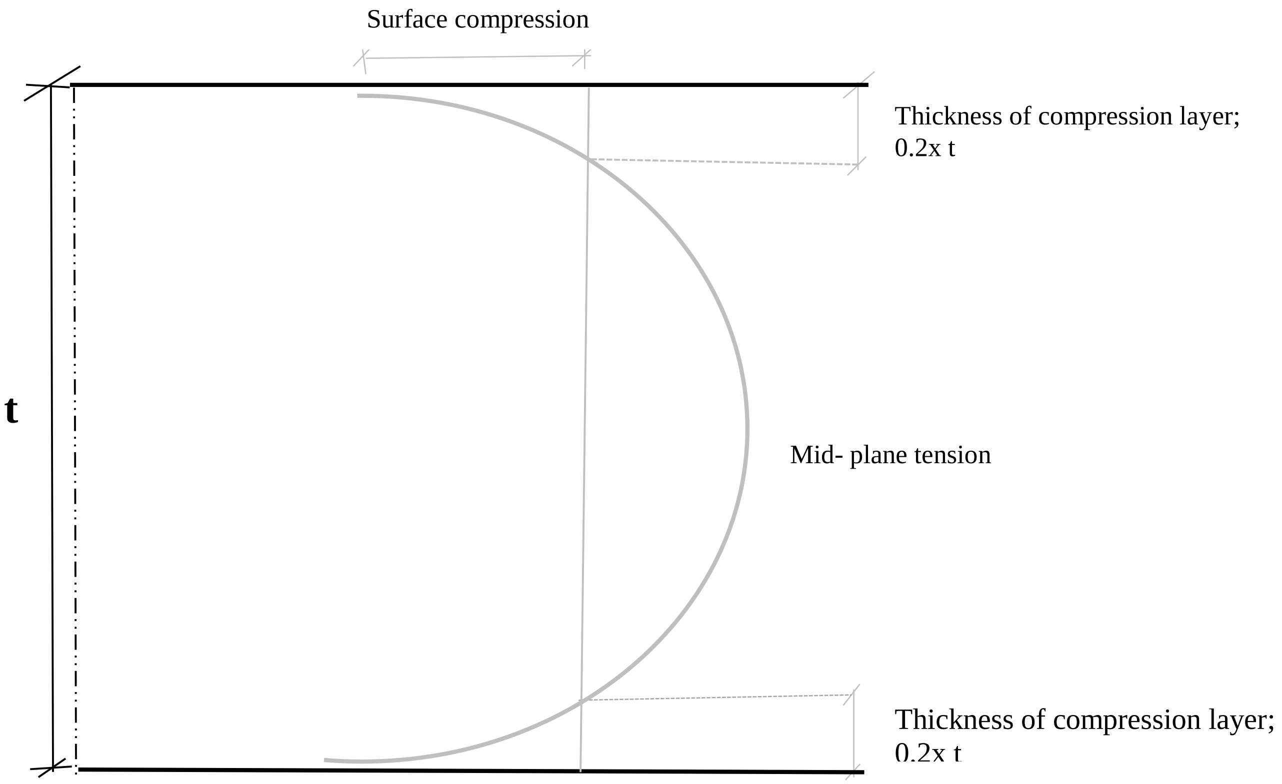


Figure 2.4: Stress distributions across the thickness of toughened glass (Naimeh K, 2004)

Bolt holes could not cause for large changes in surface stress and their diameter is at least equal to the thickness of the glass. All cutting, drilling and grinding of glass must be carried out before the glass has been toughened in order to avoid glass shattering. Tempered glass has a better performance to resistance against stress concentration at openings.

Tempered glass is susceptible to “spontaneous breakage” due to the presence of Nickel Sulphide (NiS) inside the high tensile zone at the interior. The process causing breakage occurs when α-NiS particles has been trapped in the tensile zone of the glass during production and transformed to the larger volume of β-NiS phase. As the transformation continues the volume eventually increases and induces stresses in the glass pane then it causes spontaneous breakage. To avoid this breakage the tempered glass should go through heat soak process

`

during its production because tempered glass containing NiS inclusions will break during the process and would not be put in use.

Figure 2.5: Toughened glass after breakage (source Naimeh K, 2004)

The strength of glass varies greatly depending on the particular heating and cooling cycles that are applied in its production resulting in different types of glass. The types of glass commonly used for construction are outlined in clauses (a) to (c).

Table 2.3 shows the ultimate design strength (P_u) of glass under short-term load duration. Because glass strength varies with load duration, a strength reduction factor (Y_d) should be applied to ultimate design strength (P_u) for medium and long-term load duration for various glass kinds, as shown in Table 2.4. Because the strength of glass varies depending on the glass surface treatment, the ultimate design strength should be reduced by a glass surface treatment reduction factor (γ_s) as shown in Table 2.5.

`

Table 2.3 Ultimate design strength(p_u) for different glass types under short-term load duration (Naimeh K, 2004)

Type of glass	**Ultimate design strength under short-term load duration (MPa)**
Annealed	20
Heat strengthened	40
Tempered	80

Table 2.4 Strength reduction factor(γ_d) applied to ultimate design strength for different load durations and glass types (Naimeh K, 2004)

Type of glass	Strength reduction factor (γ_d)		
	Short-term load Duration	Medium-term load duration	Long-term load Duration
Annealed	1.00	0.53	0.29
Heat	1.00	0.73	0.53
Tempered	1.00	0.81	0.66

Table 2.5 Glass surface treatment reduction factor(γ_s) for different glass types (Naimeh K, 2004)

Type of glass	Glass surface treatment reduction factor(γ_s)
Flat clear, tinted or coated glass	1.0
Ceramic fritted or enameled painted glass	0.625
Patterned (embossed), sand blasted or acid etched glass	0.5

Load resistance of a structural glass is determined by a given probability of breakage and load duration. Load duration is defined as follows:

- Short-term load duration is a load has been applied not more than 3 seconds (e.g. wind load and horizontal imposed load for protective).
- Medium-term load duration is a load has been applied more than 3 seconds, not more than 1 day (e.g. maintenance load and temperature load).

`

- Long-term load duration is a load has been applied more than 1 day (e.g. load types out of short-term and medium-term load durations).

An extruded sheet of interlayer was inserted between the glass panes during assembly. Because it is the most appropriate solution for specific applications, the glass assembly can have performance advantages over monolithic glass (BDHK, 2018). Let's discuss some glass assembly now.

a. Laminated Glass

Two or more glass panes are linked together by an interlayer to make laminated glass. Films such as polyvinyl butyral (PVB), resin, or similar are the most common interlayer materials. The thickness of the interlayer materials typically ranges from 0.38 mm to 6.0 mm. Laminated glass has been used with various types of glass and in various thicknesses. However, it is recommended to utilize the same glass type with a thickness difference of no more than one thickness grade. The edges of laminated glass must be covered from direct weather exposure in order to be considered good practice (BDHK, 2018).

Glass types, glass thicknesses, and interlayer types and thicknesses used in construction all affect the strength, breakage characteristics, and post-failure behavior of laminated glass. Laminates for structural applications are typically made up of the following materials:

- Toughened glass to enable sufficient strength to resist the applied loads; and
- Heat strengthened or annealed glass to govern the post failure behavior.

In structural laminated glasses, the film interlayer is usually polyvinyl butyral (PVB) or ionoplast. Ionoplast, on the other hand, is a thicker sheet interlayer material that is stronger and results in a stiffer laminated glass (Naimeh K, 2004).

Furthermore, the interlayer may require adequate stickiness to hold broken glass particles in the event of a failure (Figure 2.6). A number of interlayer types are available with different

`

properties that may make them more appropriate for particular applications (Tom castle, 2012)

.

Figure2.6: The interlayer holds the broken glass fragments in laminated glass (Tom castle, 2012)

b. Insulating Glass Unit

As shown in Figure 2.7, an insulating glass unit (IGU) is made up of two or more glasses that are spaced apart and hermetically sealed to form a single-glazed unit with an air space between them. IGU has been shown to be more effective in terms of sound and heat insulation.

The common form found in IGU assembly are spacer bar with desiccant filled, primary seal and secondary seal. Spacer bar shall be made of material compatible with seals and desiccant filled to enable seal durability. Primary seal is one of low permeability and serves to reduce water vapor and gas permeating the air cavity between the glass panes of IGU. Secondary seal may be two-part structural sealant which completely covers spacer with no gaps or voids continuously bonded to glass. For a good insulation, provide gaps between the two or more panes of glass and it is better when compared to the normal glass. And also filled the gaps by gases like; hexafluoride which is a good sound insulator (BDHK, 2018).

`

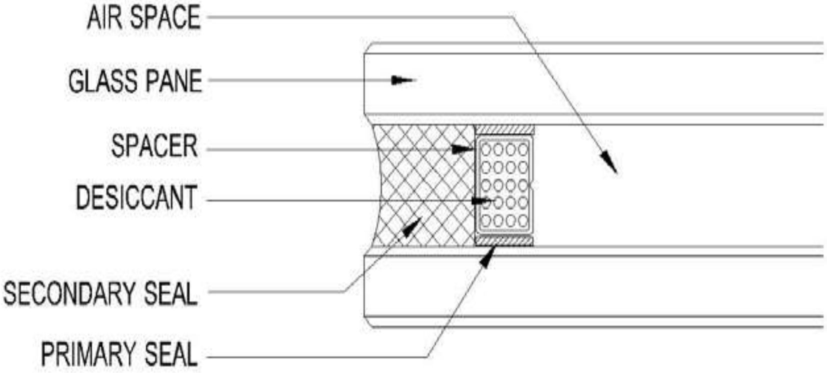


Figure 2.7: Edge of typical IGU (BDHK, 2018)

Glass façade systems has been assembled using single or multiple glass panels which is insulating glass units. Multiple glass panels can be either two or three panels which are double glazed or triple glazed as shown in Figure 2.8 and 2.9 respectively. In double glazing two glass panels have been installed into a frame with a gap between them creating a sealed unit. A spacer that separated the insulated glass unit is filled with silica balls which serve to extract moisture from the air. The benefits of double glazing installations over the single glazing;

- It prevents much of the heat escaping and reduces noise levels due to its double layers
- Can be more efficient if the gap between the two panels is slightly larger if argon is used to fill the space instead of air. Argon has a lower convection than oxygen and nitrogen occurred in the air.

Triple glazing containing a third piece of glass creating a second sealed unit into the façade system. It enables greater energy saving and increased sound insulation and it has been installed in extreme weather conditions and at locations which have a highly noisy; however, triples glazing is more expensive and heavy than double glazing.

`

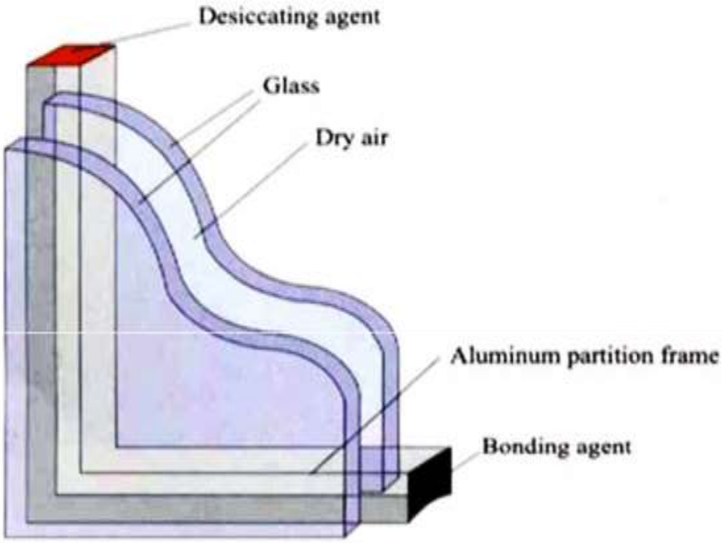


Figure 2. 8:Double glazed façade system (Pallavi & Santosh, 2015)

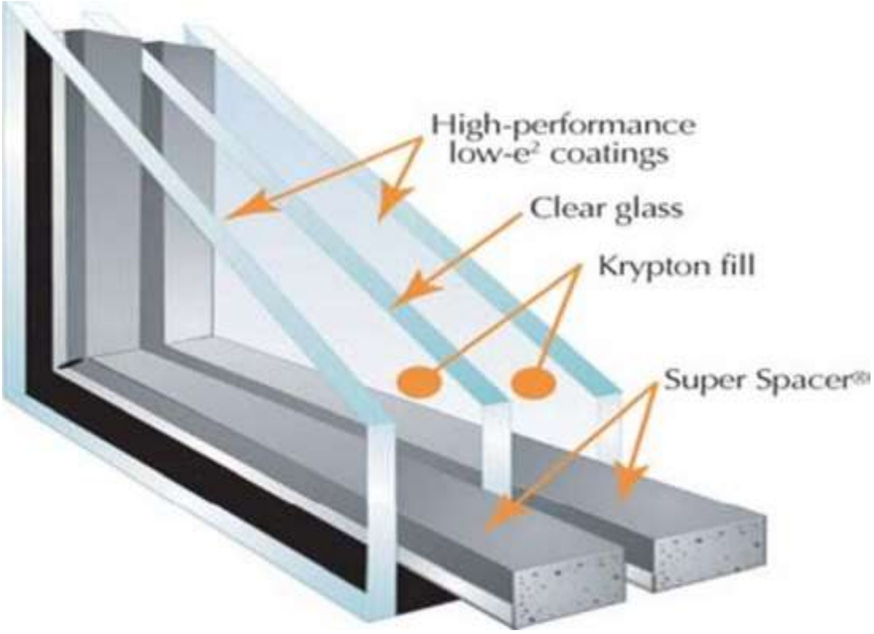


Figure 2.9: Triple glazed façade system (Pallavi & Santosh, 2015)

Thermal and acoustic performance of glass has been modified using low emissivity coating, tinting and coating. Low emissivity glass has a thin coating like metal on the glass that reflects thermal radiation or inhibits emission to reducing heat transfer through the glass. A low emissivity coating allows to pass the solar radiation through the room to reducing heat loss but allowing the room to be warmed by direct sunshine. While clear glass is the most popular glass element of insulating glass units but tinted glass may be used to reduce solar heat gain or as an architectural feature. By the use of a film or coating applied to the surface of glass can be improved the heat and sound insulation of glazing. This film has been typically made of polyester or metal and it gives the window a reflective mirrored appearance.

The analysis methods should be based on as accurate a representation of the structure's behavior as is reasonably practicable. The main goal is to arrive at a set of forces and moments that are in balance with the design loads produced by the load combinations. In general, it is satisfactory to determine the forces and moments by linear analysis or nonlinear analysis where appropriate for ultimate limit state and serviceability limit state.

As the effect of change in the geometry under loads is significant in thin glass panes, the advanced large deflection method of analysis is more accurate and computer programs are widely used for this type of analysis. For irregular shaped glass panes, the finite element method should be used for linear and large deflection nonlinear analysis. For glass panes with small thickness, it would be subject to the nonlinear effects from the membrane stress due to out-of-plane deflections in addition to the bending stress.

In the determination of the stress and the deflection for the design purpose, the minimum glass pane thickness should be adopted as specified in Table 2.6.

Table 2. 6.Glass thicknesses for analysis and design (BDHK, 2018)

Nominal glass pane thickness (mm)	6	8	10	12	15	19	22	25
Minimum glass pane thickness , t (mm)(for analysis and design)	5.56	7.42	9.02	11.91	14.2	18.26	21.44	24.61

`

2.3. GLASS FAÇADE SYSTEMS

Depending on the structural support, a glass façade system (GFS) can be classified as a framed glass façade system (FGFS) or a frameless or point-fixed glass façade system (PFGFS).

2.3.1. Framed Glass Façade Systems

Although the early curtain walls were made of steel, framed glass façade systems (FGFS) are often created using extruded aluminum members. In most cases, the aluminum frame is filled with glass, which creates a pleasant envelope as well as natural daylight. These façades were designed to span multiple floors and to meet design requirements such as thermal expansion and contraction, building sway and movement, water proofing, and thermal efficiency for cost-effective heating, cooling, and lighting.

The three most common forms of aluminum glass façade systems are conventional (stick), semi-unitized, and unitized (Gerd H, 2017).

a. Conventional (Stick) System

The stick system was the first curtain wall design. This facade is being installed one piece at a time. The mullion members (vertical members) are typically installed first, followed by the transom members (horizontal rail members), and then the glazing or window units.

The following are the characteristics of the conventional stick system:

- The vertical mullions and the horizontal transoms are installed or bind on brackets and anchored to the slab or beam of the structure.
- The glass is fixed in the grid work with pressure plates (the glass has been glazed mechanically)
- The components of this system are assembled on the site
- It can be vary depend on the site conditions.
- It takes high field cost

- It has longer installation period because the system is completely assembled on site.

Its drawbacks include the need for assembly on the job site rather than in a controlled factory environment, as well as the fact that pre-glazing is clearly impossible.

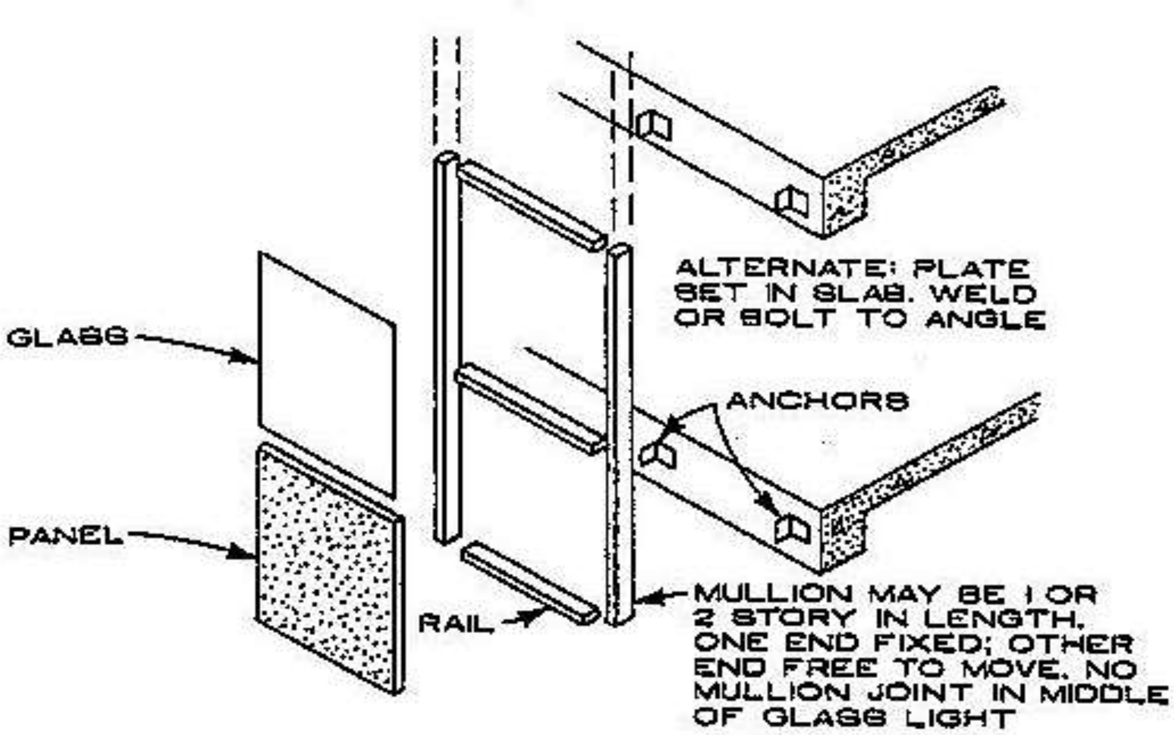


Figure 2.10: Diagram to illustrate the stick façade system (Gerd H, 2017).

b. Semi-unitized System or Unit Mullion System (Hybrid system)

Semi-unitized design appeared in façade system technology after a period of time. When all of the panels are assembled at the factory, quality may be achieved, but when it comes to the glass, which is placed on site, quality is extremely difficult to achieve.

The following are the characteristics of the semi-unitized system:

- Brackets are anchored to the columns or slabs after detailed the survey.
- The complete unit spanning floor height has been fully fabricated at the factory is installed on the brackets.
- 10% of the work has been done at the site when compared to stick system.

- Comes pre- assembled mean that its frame installed in the factory and it is glazed on site.
- It can minimize field labor, erection costs and installation period.

A hybrid system is advantageous when there is a long span between two floors that can be reinforced with steel.

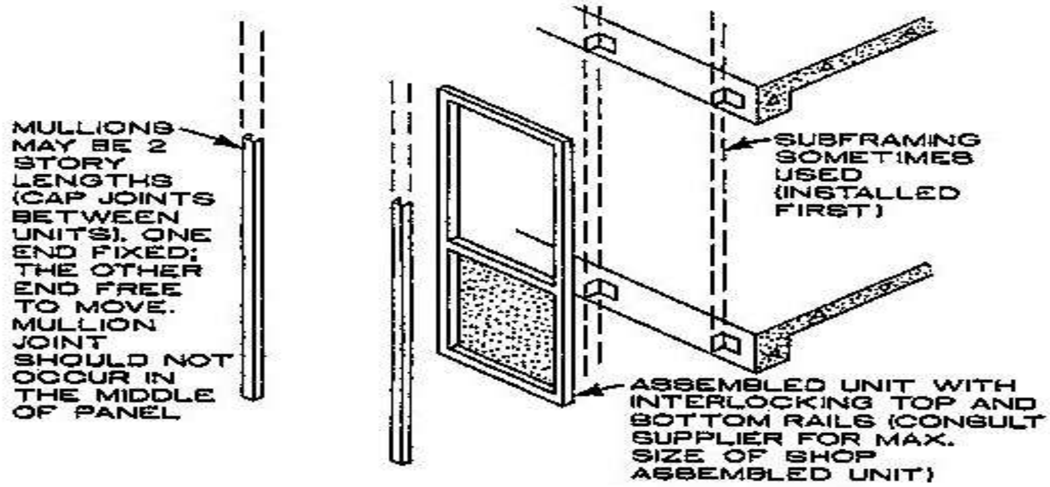


Figure 2.11 : Diagram to illustrate semi-unitized façade system (Gerd H, 2017).

c. Fully Unitized System/ Unitized panel system

The unitized façade system was created for modern technology. This system is made up completely of factory-assembled massive frame pieces. It is floor to floor height, and these panels, together with the glass, were built at the factory and transported to the job site.

The following are the characteristics of the unitized system:

- The vertical mullions and horizontal transoms are installed on the brackets and anchored to structural slab or beam.
- Glass is structurally glazed to the aluminum sub frame by structural sealant and these sub frames has been fixed in the grid work
- Minimize the cost and lead a shorter time because there is minimum customization
- Labor time at the field and costs for erection are more in line with stick system.

`

As a result, a unitized system maintains the highest quality and requires much less manual work on the job site.

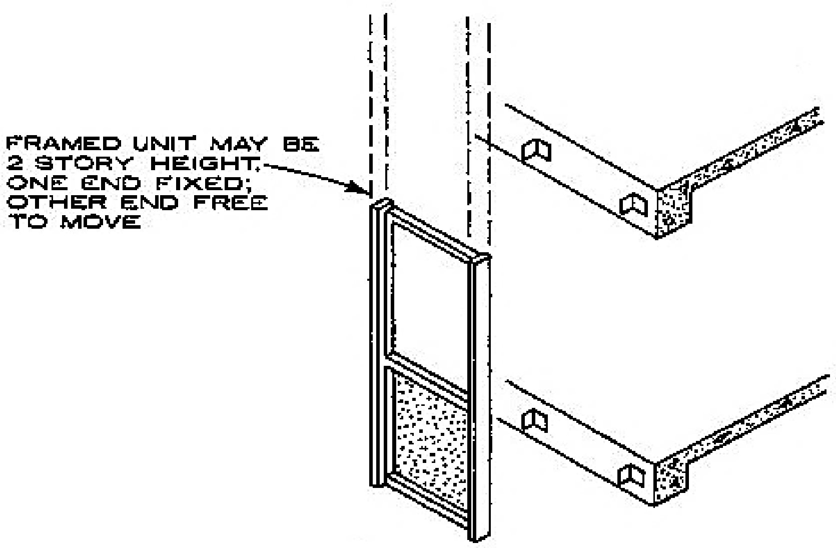


Figure 2.12: Diagram to illustrate unitized curtain wall system(Gerd H, 2017).

2.3.2. Frameless Glass Façade System

Due to the growing number of architects, framed glass façade systems have been replaced with frameless glass façade systems. This method could allow more natural light into buildings. By removing the mullions and aluminum profiles, this provides a distinct advantage in terms of transparency and having a planar glass surface. This method can also use double glazing to improve energy efficiency by increasing insulating capacity (Jose S. 2013).

Modern frameless glass façade systems are frequently bolted together with spider arms steel structural support frames, which are important architectural elements that combine structural stability and aesthetic expression. The glass panels are held in place by the bolted spider arms connectors. Point fixed glass façade systems (PFGFS) are used in a variety of constructions, ranging from simple storefront shop windows to more complicated multi-story buildings and large atriums. The bolted fixings were placed around the glass panels' corners, as well as at intermediate points along their long sides.

`

Point-fixed glass support systems include truss systems, cable systems, and steel-supported systems, all of which are made up of four fundamental components: glass panels, bolted fixings, glass support attachments (spider arms), and the main structural support frame (Jose S. 2013).

- Point fixed glass on base supported steelwork such as simple posts, trusses and fins as shown in Figure 2.15 (a) and 2.15(b).
- Point fixed glass on cable systems where the structural support frames are nearly entirely made of tension elements such as rods or wires and are both physically and visually light. Loads must be transferred to boundary structural support frames at both ends of the cables. Figure 2.15 (c) shows how the weight of the vertical glazing is supported by a tie rod hanger system or by each panel being suspended from the panel above it.
- Glass beams or fins supported one-way spanning glazing on fin walls: The glazing was attached intermittently using bolted connections as indicated in Figure 2.15 (d).

Figure (a) .Simple post supported PFGFS at a storefront in Melbourne

`

Figure (b). Truss supported PFGFS covering a 4-storey building

Figure (c). Cable supported PFGFS

Figure (d) Glass fin supported PFGFS at Swinburne University

Figure 2.13: Frameless façade systems (Jose S. 2013)

`

2.4. THE EFFECTS OF NATURAL FORCES ON THE FAADE SYSTEM

Obviously, all exterior walls, whatever the material, are susceptible to the ravaging effects of nature and must resist them. Before the discussion of the design of a curtain wall system, let's look at the effects of the natural environment.

2.4.1. Sunlight

Humans could not survive without sunlight. Warmth, color, visual definition, and life itself are all provided by it. However, it causes some issues with curtain wall design. One of these issues is that it destroys organic compounds, including color pigments, plastics, and sealants.

Actinic rays, particularly those in the ultra-violet spectrum, create chemical changes in materials that cause fading or more serious damage. It is also critical that materials and finishes that are subject to such action be thoroughly examined before being used, and that sealants be tested for ozone and ultraviolet radiation resistance (AAMA, 1996).

Another problem that arises when uncontrolled sunlight passes through the wall is glare and brightness, as well as the degradation of interior furnishings.

Traditionally, similar effects have been countered by the use of a shade mechanism, either inside or outside the vision glass. The use of glare-reducing or reflecting forms of glass, which provide relief without restricting vision, is a modern strategy that is gaining popularity.

2.4.2. Temperature

In curtain wall design, temperature creates two types of problems:

- the expansion and contraction of materials; and
- the need to control the flow of heat through the wall.

One of the major concerns in aluminum curtain wall design is thermal movement, which is caused by the effect of solar heat on the wall. Temperature variations, both diurnal and seasonal, have a significant impact on wall details. Temperature changes cause all building

`

materials to expand and contract to some extent, but aluminum expands and contracts more than most other building materials.

Heat loss in cold weather and heat gain in hot weather are both affected by the control of heat flow through the wall, with the relative importance of the two differing depending on geographic location.

When opaque wall areas account for a significant portion of the total wall area, thermal insulation becomes an important consideration; however, when vision glass areas predominate, the use of insulating glass and the elimination of through metal or "cold bridges" are more effective in lowering the overall U-value of the wall.

2.4.3. Water

The most persistent source of potential trouble is water, which comes in the form of rain, snow, vapor, or condensate. It can enter very small openings, migrate within the wall, and appear on the indoor face far from its point of entry as wind-driven rain. It can penetrate microscopic pores as vapor, condense upon cooling, and, if trapped within a wall, cause serious damage that may go undetected for a long time (1999, Quirouette).

Leakage can occur in a wall made of any material. Because most masonry walls are porous, they absorb a lot of water over their entire wet surface, especially in certain conditions. Some of this water may penetrate through the wall and cause leaks on the inside. Metal curtain wall materials, on the other hand, are water-resistant, and any leakage is limited to joints and openings. Though this reduces the exposure area, it emphasizes the significance of properly designing the joints and seals.

`

2.4.4. Wind

The forces produced by wind acting on the wall are significantly responsible for its structural design. Maximum wind loads determine the structural properties of frame members and panels, as well as the thickness of glass, on taller structures in particular.

Winds also play a role in wall movement, affecting joint seals and wall anchorage. High winds create pressures and vacuums that cause stress reversal in framing members and glass, as well as causing rain to defy gravity and flow in all directions over the wall face. As a result, wind must be considered as a key contributor to potential water leakage.

2.4.5. Gravity

Unlike the other natural forces, gravity is constant and static, rather than dynamic and variable. Because of the light weight of the materials used in curtain walls, it is only a little force that rarely causes serious design problems. It causes deflections in horizontal load-carrying members, especially under the weight of large sheets of heavy glass. However, because the weight of the wall is transferred to the building frame at frequent intervals, gravity forces affecting structural design are generally small in comparison to those imposed by wind action. However, the building structure to which the wall is linked is subjected to significantly greater gravity forces in the form of floor and roof loads. Because these loads may produce deflections and displacements in the frame, the wall's connections to it must be built to allow for enough relative movement such that displacements do not impose vertical loads on the wall.

`

2.5. DESIGN CONSIDERATION

A curtain wall system is a cladding system made up of continuous elements that loop around the building structure like a curtain, excluding wind and weather, allowing for air conditioning, but not resisting building loads. It typically consists of an aluminum frame structure with glass vision panels and spandrels made of any panel material, such as glass, metal, stone, compressed cement, or sandwich panels. Curtain wall systems must meet various performance standards prior to structural analysis in order to perform satisfactorily.

The major problem areas to be expected are identified by analyzing the influence of these natural forces. Experience has shown that there are three primary issues to consider when designing a unitized curtain wall system. They are;

- structural integrity;
- provision for movement; and
- weather tightness.

Of course, there are a number of other factors to consider, the majority of which are minor and some of which change in importance depending on the location and type of building. Let's take a quick look at the major considerations that apply in all cases.

2.5.1. Structural integrity

The structural integrity of the wall may be stated to be the primary concern in its design because structural failure may risk human life. However, curtain wall structural design follows the same procedures as any other wall, and deficiencies in this area are less likely to arise than deficiencies in providing for movement and weather tightness requirements, which present unique challenges in metal construction. In most cases, structural requirements for stiffness rather than strength govern, and while excessive deformations may cause damage in some

`

cases, the few instances of actual failure that have occurred have been limited to incorrect anchorage details.

Because the wall system's vertical loads are very small, structural design is primarily concerned with providing adequate resistance to lateral wind forces. If the nature and magnitude of the wind loads are known, this is a simple procedure. However, this could be the source of the issue. Wind loads on low and medium-rise buildings are fairly well understood, but there is still much to learn about the nature and intensity of such loads on tall structures.

Maximum wind velocities, and thus design wind loads, vary not only with geographic location but also with height above the ground, which is very well known. The characteristics of the building's surroundings, such as suburban character or dense urban development, is less well recognized as having a greater impact on wind action. Another truth that is not well recognized, even by some of the major building codes, is that the wind loads acting on the building's skin are of a different nature and magnitude than the wind loads that govern the design of the building frame. Those acting on the wall are more severe in intensity, have a specific rather than cumulative effect, and change more dramatically and faster than the overall design loads (AAMA 1996).

Negative wind loading, or suction forces, acting on the wall are usually ignored, despite the fact that internal building pressures from air conditioning may increase such forces. Many designers think only in terms of wind pressure, when in fact, even in moderate winds, more of a rectangular building's total perimeter wall surface is likely to be exposed to a vacuum than to pressure.

Negative pressures are usually highest near the building corners of high-rise buildings, where they can be more than twice as great as any positive load on the wall. When wind damage does occur, it usually occurs as a blow-out rather than a blow-in.

`

This explains why the most common error in structural design is a failure to provide adequate resistance to the suction action of the wind, particularly in anchorage details.

2.5.2. Provision for movement

The ability to move freely is a critical consideration in the design of any aluminum curtain wall. There is no such thing as a static building, and the metal curtain wall is no exception. Movement occurs all the time, including movement inside the wall components, relative movement between components, and relative movement between the wall and the building frame to which it is attached. Temperature variations, as well as wind, gravity forces, and deformations or displacements in the building frame, all contribute to these movements. Ignoring such movements while designing the wall is a surefire recipe for trouble. Because of aluminum's very high coefficient of expansion, temperature changes have a particularly significant effect, but the amount of movement is predictable. The likely seasonal range of metal surface temperature in most parts of the country is at least 150°F, and in some places it may be as much as 200°F. In a 10-foot length of aluminum, this translates to a movement of 1/4” to 5/16”. The amount of movement in a sheet of glass used alongside the aluminum will be less than half as much (Quirouette 1999).

Movement caused by the other factors mentioned is often unpredictable, but it can be just as significant. Whatever the cause, the problem of providing for movement comes down to joint design, because movement must be accommodated at the joints. As a result, it becomes self-evident that the key to a functionally successful curtain wall is the design of its joints.

As a result, the most important, and sometimes the most difficult, part of any curtain wall design is the joint details. However, utilizing larger wall units and hence fewer joints does not always indicate that the problem will be solved. This is almost never the case. The more movement that must be allowed at each joint, the larger the units or the longer the members, tends to complicate rather than simplify joint design.

`

Of course, vertical and horizontal movement in the plane of the wall must be provided, either through slip joints or bellows action. It should be recognized, however, that expansion and contraction do not always translate into displacement. Increased stress within the member can sometimes absorb them, at least to some degree, resulting in calculated deformation, and they are frequently accommodated by a combination of stress and deformation. Except in a few cases, reliance upon stress increase to accommodate expansion is not recommended, as it may result in excessive bending or buckling.

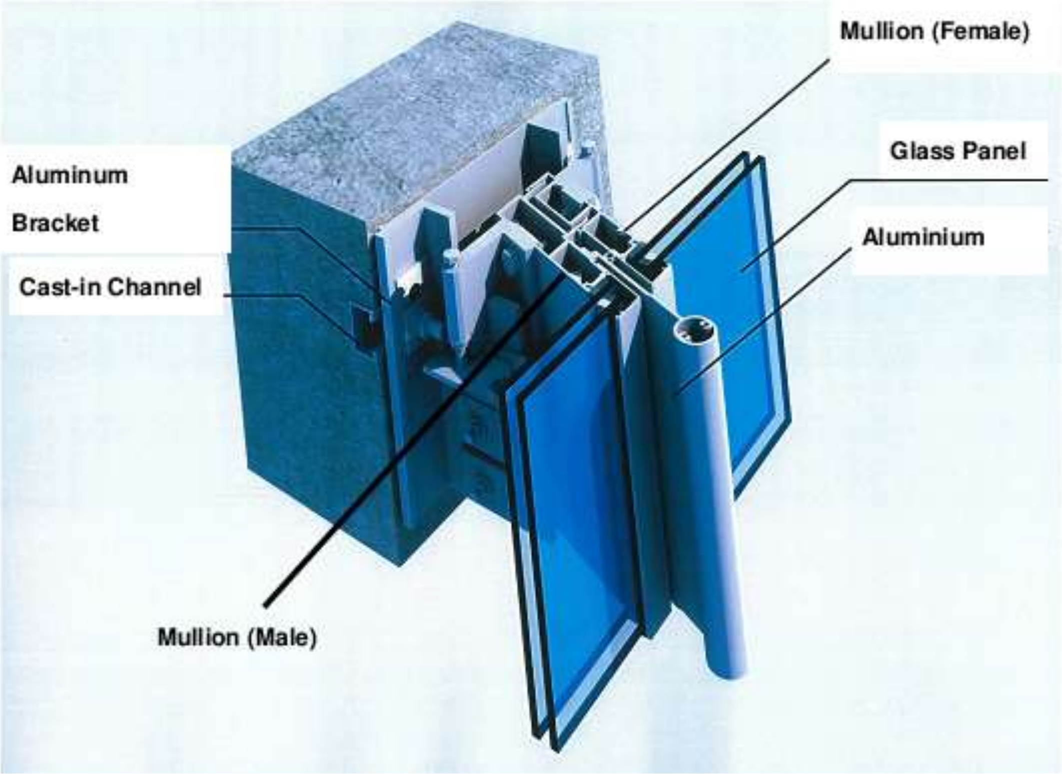


Figure 2.14: Fixing details of unitized curtain wall system

Figure 14 depicts the fixing detail of a unitized curtain wall system with a slot hole design at the connection; this design takes into account the system's movement and concrete tolerance. The male mullion denotes the vertical member of the left side unitized curtain wall panel, while the female mullion denotes the vertical member of the right side unitized curtain wall panel.

`

2.5.3. Weather tightness

Water leakage and excessive air infiltration are both prevented by weather tightness. It is mostly dependent on adequate mobility provision and is tightly linked to good joint design. Without a doubt, the lack of weather tightness has been a key source of problems with aluminum curtain walls over the years. Water leakage was all too common in elderly walls, due to faulty design, materials, or workmanship, or a combination of these factors. However, due to advanced materials and design techniques, prevention is now the rule rather than the exception. Excessive air leakage, on the other hand, is less harmful and easier to prevent.

Rainwater flows in all directions over the windward surface of a panel under strong wind loads, and on impermeable surfaces, much of it collects at the joints, which are the most vulnerable areas. Because of the constant movement of metal curtain walls, it became clear early on that providing a permanently waterproof seal on their outer surface was basically unachievable, and this approach to weather tightness was quickly removed.

Instead, two other methods for preventing leakage through the wall have been discovered, and either of these is highly reliable when used correctly. One is recognized as the 'internal drainage' or ‘secondary defense' system, and it's been used by competent designers for a long time, as seen in Figure 16.

The other is the ‘pressure equalization' method, which is a relatively new invention in metal curtain wall technology (see figure 17).

The internal drainage method is based on the belief that it is impractical, if not impossible, to completely eliminate all leakage at all points in the outer skin of the wall for any length of time, but that minor leakage can be prevented from penetrating the interior face of the wall or remaining within the wall.

`

This is accomplished by utilizing a system of flashing and collection devices in the wall itself, as well as enough drainage outlets on the wall's exterior face.

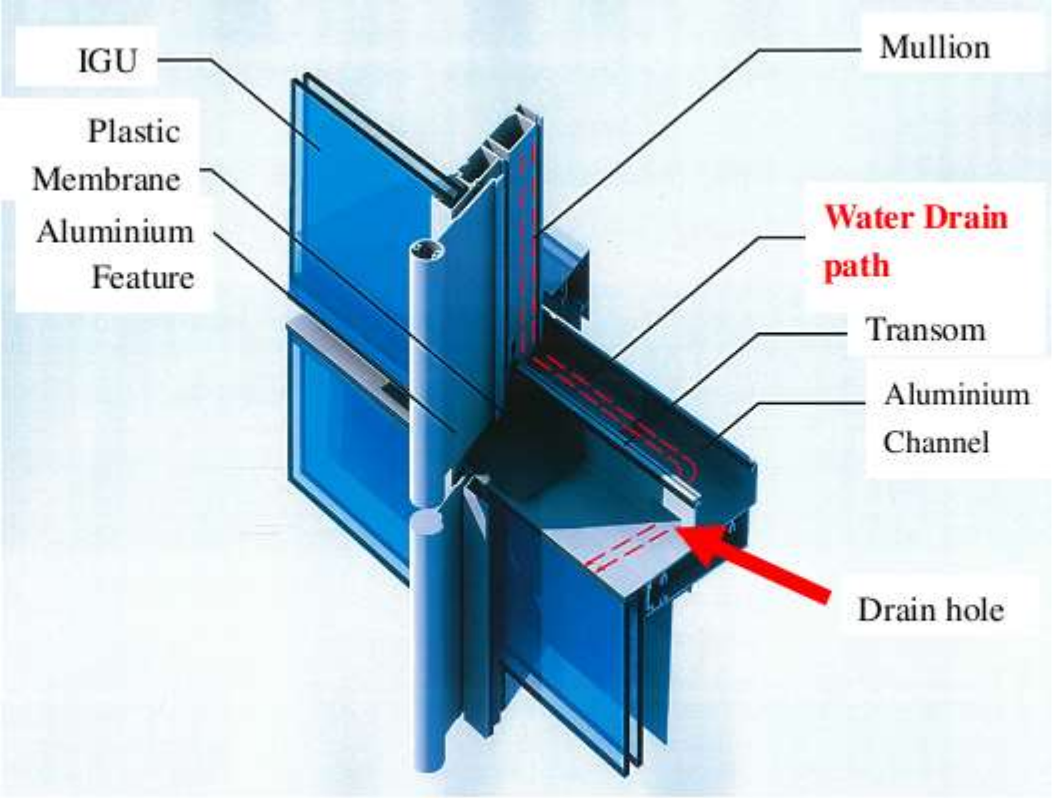
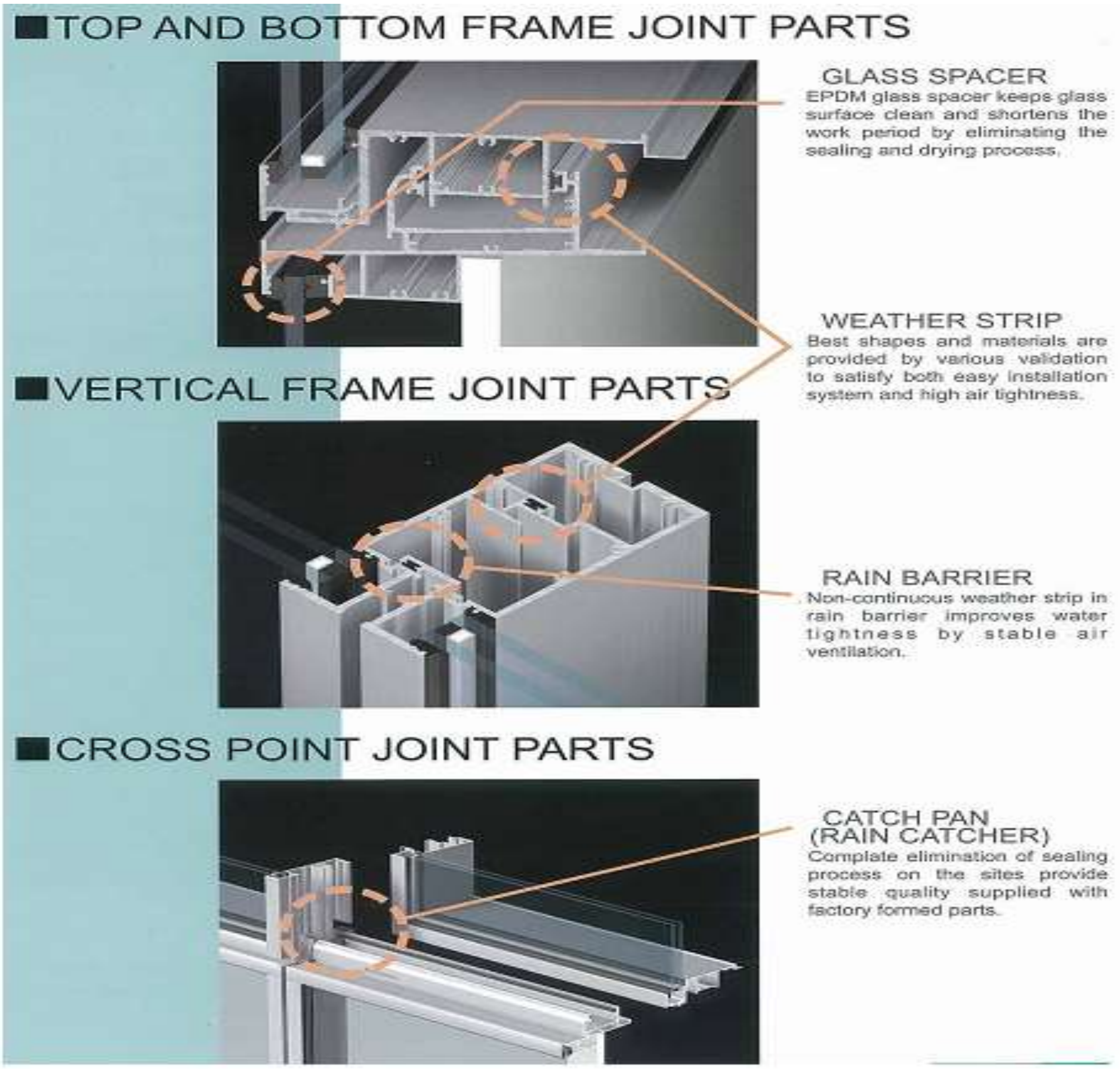


Figure 2.15: Drainage path in unitized curtain wall system

`



TOP AND BOTTOM FRAME JOINT PARTS

GLASS SPACER
EPDM glass spacer keeps glass surface clean and shortens the work period by eliminating the sealing and drying process.

WEATHER STRIP
Best shapes and materials are provided by various validation to satisfy both easy installation system and high air tightness.

VERTICAL FRAME JOINT PARTS

RAIN BARRIER
Non-continuous weather strip in rain barrier improves water tightness by stable air ventilation.

CROSS POINT JOINT PARTS

CATCH PAN
(RAIN CATCHER)
Complate elimination of sealing process on the sites provide stable quality supplied with factory formed parts.

Figure 2.16: Design concern of weather tightness in unitized curtain wall system

The ‘rain screen principle' method of pressure equalization is a more sophisticated and complex approach, but it is claimed by its supporters to be totally accurate when properly applied. It required the installation of a ventilated outer wall surface backed by drained air spaces with pressures equal to those outside the wall, as well as the sealing of the wall's interior face against air passage. Figure 15 depicts one example.

`

The successful application of these methods requires a thorough understanding of how wind-driven rain works, careful detailing, and, of course, proper installation. And in both cases, strategically located and well-baffled weep holes or drainage slots are critical.

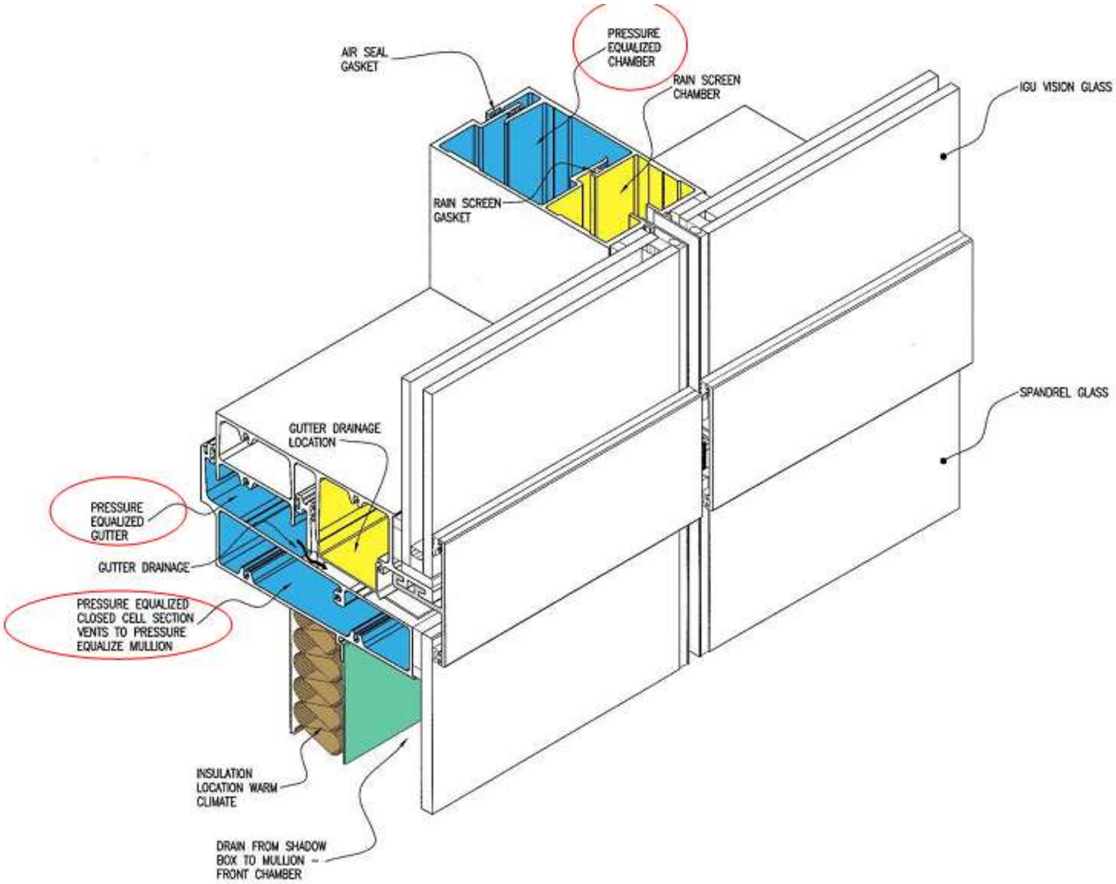


Figure 2.17:Design concern of pressure equalized in unitized curtain wall system

2.5.4. Moisture control

Controlling condensation is critical in any aluminum curtain wall design, since aluminum and glass are not only resistant to moisture and hence effective vapor barriers, but they also have a low heat retention capacity.

Moisture, or even frost, may form on the inside face of the wall if proper controls are not in place, and condensation may collect within the wall, causing considerable damage before it is

`

detected. Fortunately, controlling moisture is a relatively simple task if the problem is anticipated and preventative measures are built into the wall when it is built.

If difficulty is to be avoided, it is important to understand the causes of condensation, where it will most likely occur, and how to reduce its potential damage. However, explaining these issues is beyond the scope of this overview, which is simply meant to highlight the relevance of the matter. The following are the critical precautions to remember in capsule form:

- A vapor barrier should be placed on or near the interior side of the wall;
- Impervious internal surfaces should be adequately insulated to keep them warmer than the dew point of the air touching them;
- Provision should be made for vapor to escape to the outdoors; and
- The wall should be detailed in such a way that any condensation that forms within it is collected and drained away.

2.5.5. Thermal insulation

Figure 18 shows how the insulating value of a wall can be one of the most important design factors in some cases. Reducing the total U-value of the wall is usually a beneficial long-term investment, whether it's to reduce heat loss and prevent condensation in cold weather or to minimize heat gain and air conditioning costs in hot weather. Aluminum and glass are heat-conducting materials by nature, but with careful attention to detail, aluminum curtain walls can be designed to provide good thermal performance. In general, this is accomplished by reducing the amount of aluminum framing members exposed to the elements, using ‘thermal breaks' to eliminate thermal short circuits, using double glass rather than single glazing, and providing adequate insulation in large opaque areas of the wall.

`

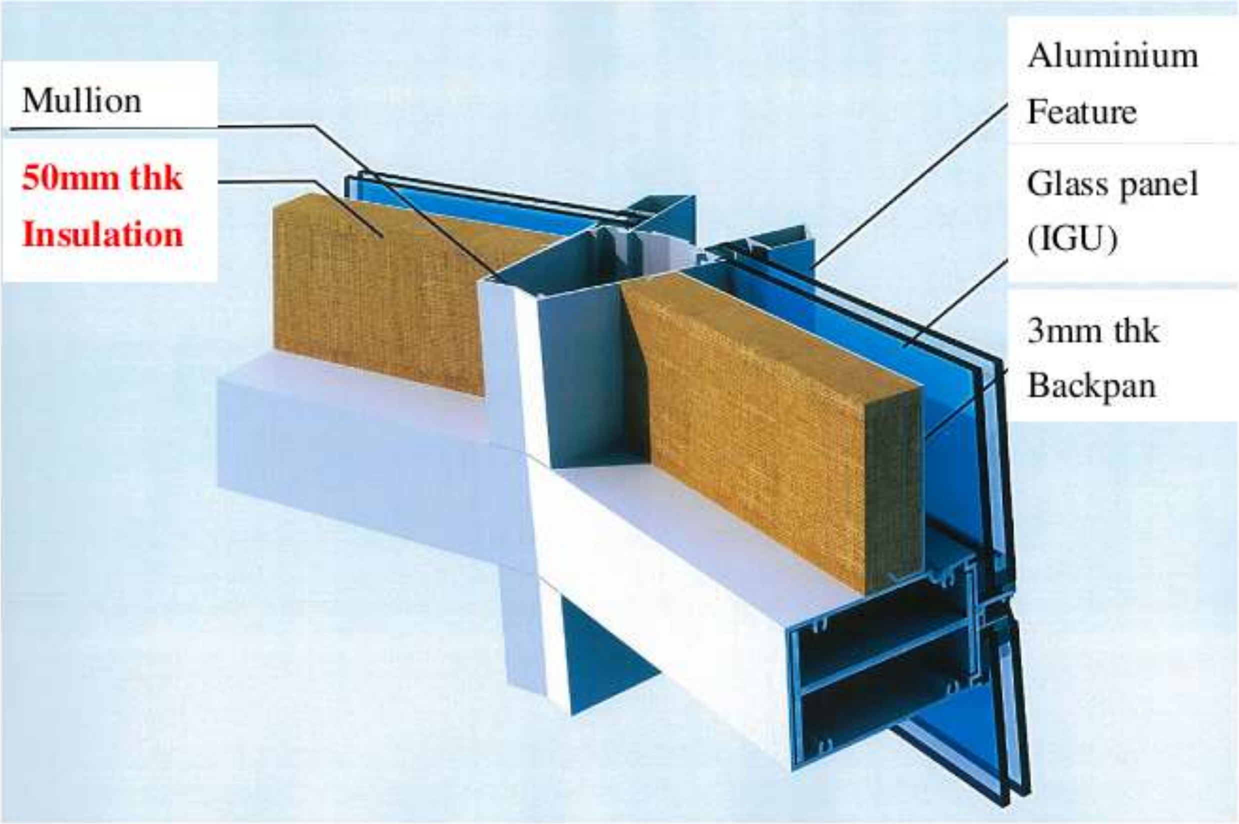


Figure 2.18: Insulation installed in unitized curtain wall system

2.5.6. Sound transmission

Metal curtain walls compare favorably to any other wall construction with a similar façade as a barrier to airborne sound under typical conditions, even in densely built urban areas. The increasing worry about noise pollution, as well as the development of buildings near airports, has brought attention to the need for ‘soundproofing' exterior walls.

According to the law of mass, sound transmission through any barrier is inversely related to its mass, hence a lightweight construction like an aluminum curtain wall has no natural advantage as a sound barrier. Aluminum curtain walls have been designed to create quiet enclosures near several airports with careful details and an understanding of sound transmission principles.

It's important to remember that the effectiveness of an airborne sound barrier is mostly determined by its weakest link, and the weakest links in most walls are glazed areas and openings, no matter how small they are. When a high level of sound insulation is required, air leakage through the wall must be reduced, which usually requires double glazing that is well separated and sealed.

2.6. GLASS CONNECTION

Contact with glass and any other hard substance with a harder than glass should be avoided if possible. With frame systems, gaskets or other glazing materials should be used. It is critical to ensure that the glass does not come into direct contact with the bolt or clamping plates when bolted connections are used. A proper bushing material must be used, with a hardness lower than that of the glass (BDHK, 2018).

2.6.1. Framed Infill Glass Pane

The framed section should provide a minimum of 10 mm edge cover, a minimum 6 mm edge clearance, and a minimum 5 mm front and back clearance to the glass pane for fully framed or two-edged framed infill glass panes, as indicated in Figure 2.21. The thickness of the edge cover should not be less than the thickness of the glass pane in contact.

The framed section, as well as its connections to the main frame, should be able to withstand the design load that is transmitted through the glass panes.

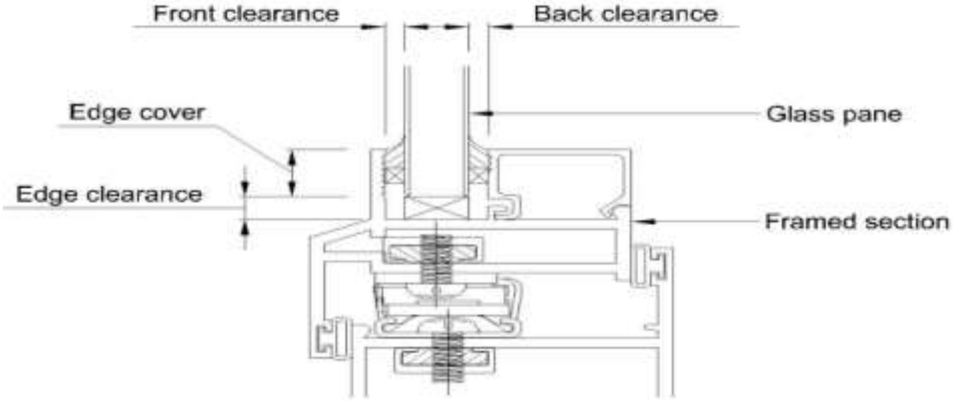


Figure 2.19: Edge cover and clearances of framed infill glass pane (BDHK, 2018)

`

2.6.2. Adhesive based connection

The use of silicone to make glass-to-glass right-angle butt connections is one of the most common types of adhesive connection. As such fixings allow the glass to rotate within the frame, they are regarded as simply supporting such a glass connection design.

2.6.3. Point bolted supports

Tempered glass should be used, and the connectors should be positioned so that the glass panes do not undergo reverse curvatures, as this could lead in extremely high stress concentrations at bolted connections. Clamping plates and gaskets should be installed on both sides of the glass panes to give a minimum 50 mm diameter cover. When the length of a glass pane exceeds the span between the bolted connectors, a cantilevered portion of the glass pane should be less than one-quarter of the span between the bolted connectors.

The bolted connections' attachment to the main frame should be strong enough to bear the design loads transmitted through the glass panes.

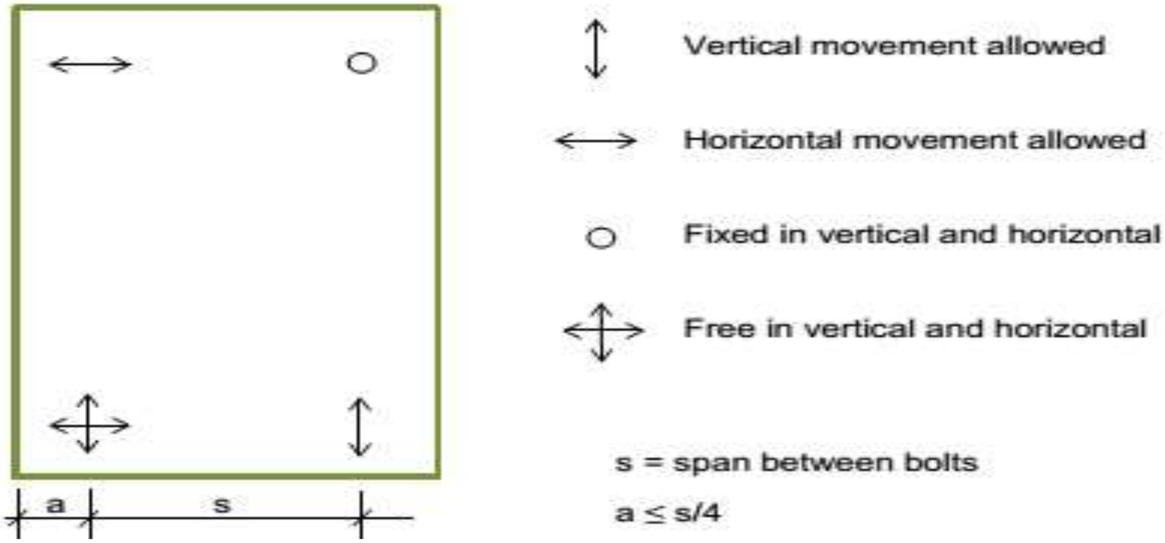


Figure 2.20: Allowable in- plane movements at bolted connections

`

2.6.4. Clipped infill glass pane

Clips should be positioned around the periphery of infill glass panes, with a maximum X spacing of 600 mm between fixes for clipped infill glass panes. Each glass pane must have a minimum of four fixings. The clips should not be more than X4 away from the corner. Each clip should be at least 50 mm in length and cover the glass panes to a depth of at least 25 mm. The clips, as well as their connections to the main frame, must be able to withstand the design loads that are transferred through the glass panes. Figure 2.23 shows a typical clip arrangement.

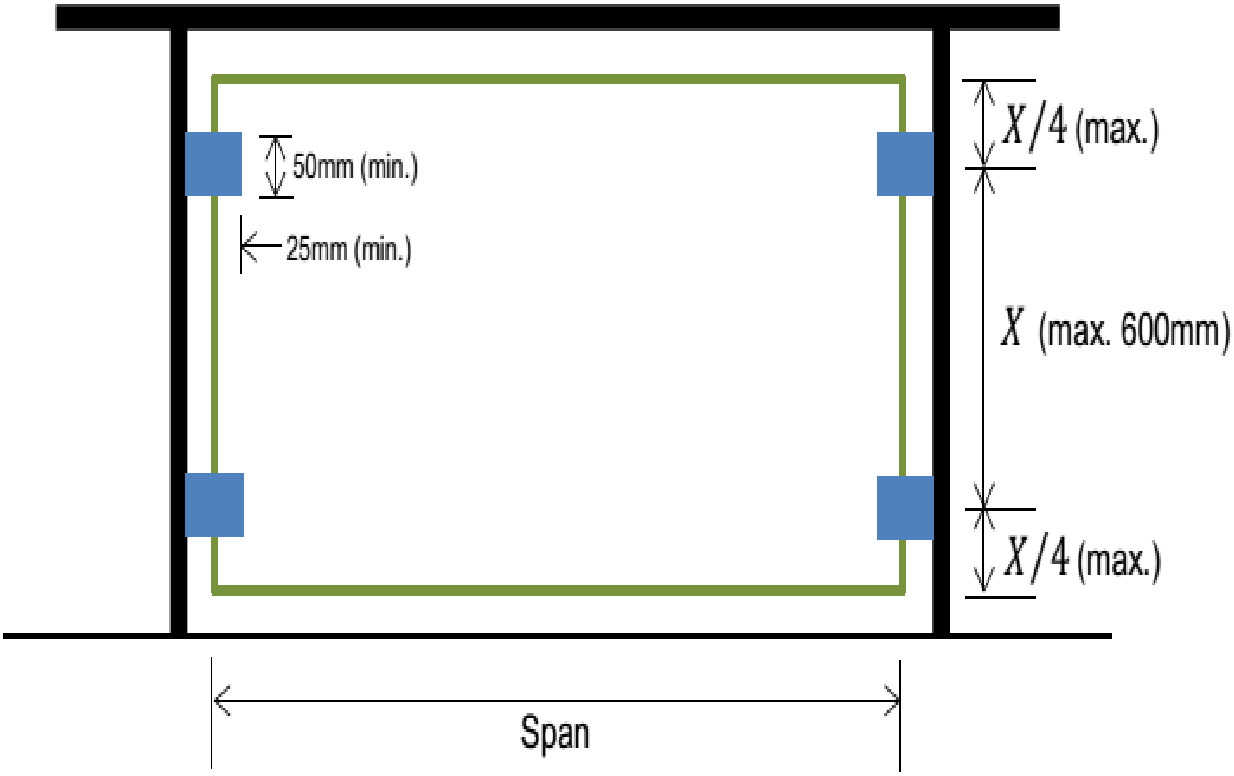


Figure 2.21: Clipped infill glass pane

`

2.7. HOLES IN GLASS

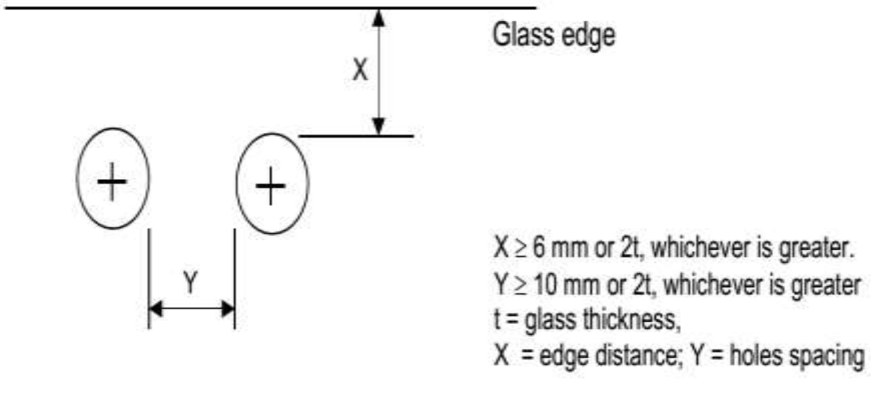
In general, the existence of holes causes stress to concentrate on the glass pane, which should not be ignored. Under tensile load on an infinite thin plate with a hole, conventional peak stresses around the hole can be up to three times the stress away from the hole.

To provide a more accurate assessment of stress concentration effects at the contact area of the hole opening or notch in the glass pane, a rigorous finite element analysis of the glass pane with hole opening or notch should be conducted for glass panes under lateral loads and supported by bolting and point fittings. Since this design is based on well-defined parameters, no specific test is required to demonstrate the bolted connection's structural performance. Attention should be paid to the bolt/glass contact of the bolted connection, as well as the placement of holes that should be filled with a sufficient thickness of less stiff resilient gasket.

2.7.1. Placement of holes

Figures 2.24 to 2.26 show the dimensions and locations of the holes in glass.

1) The minimum distance between any edge of a glass pane and the nearest point on the rim of a hole must be 6 mm or twice the glass thickness, whichever is greater.
2) The minimum distance between adjoining hole rims must be 10 mm or twice the thickness of the glass, whichever is greater.



$X \geq 6$ mm or 2t, whichever is greater.
$Y \geq 10$ mm or 2t, whichever is greater
t = glass thickness,
X = edge distance; Y = holes spacing

Figure 2.22: Placement of holes

3) When the corner is 90° or more, holes near corners must be located so that the nearest edge of the hole is at least 6.5 times the thickness of a glass pane from the tip of the corner.

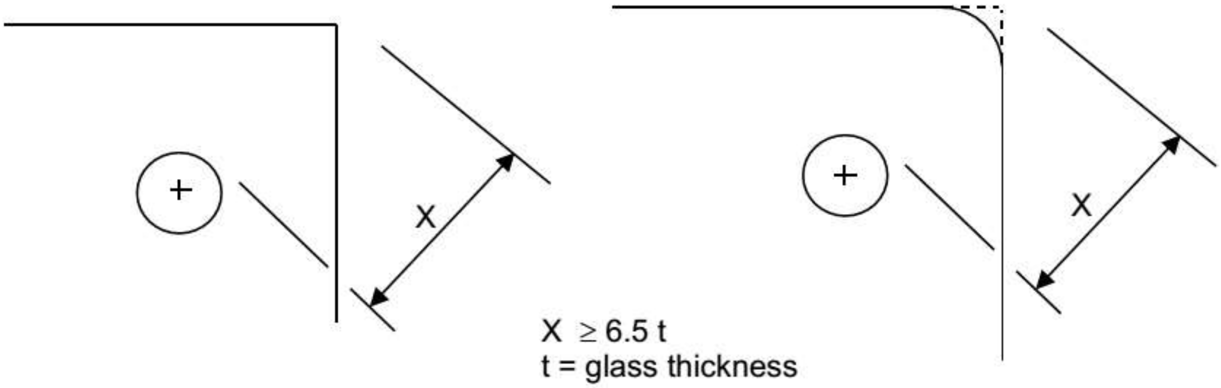


Figure 2.23: Location of holes near corners

4) Minimum hole dimension-Circular holes must be at least 6.4 mm in diameter or the thickness of a glass pane, whichever is greater. Any corners, other than circular holes, must have fillets with a radius equal to or larger than the thickness of the glass pane.

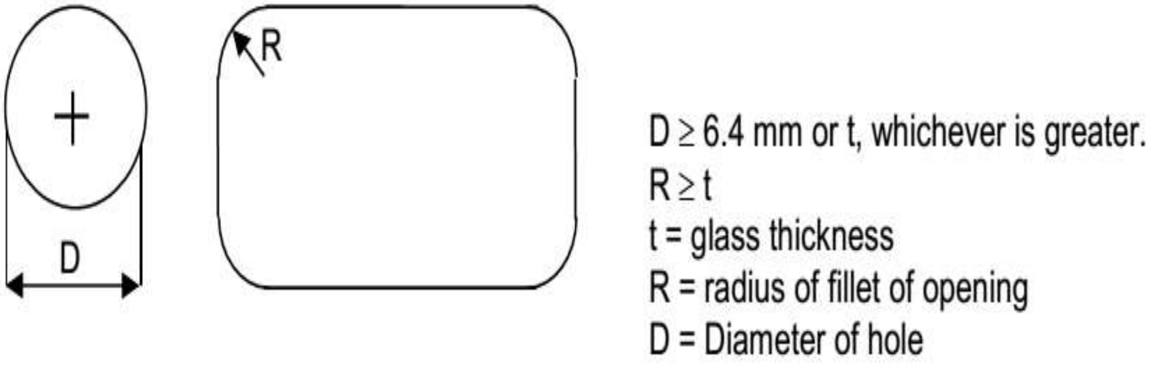


Figure 2.24: Minimum dimension of holes

`

2.8. INTERLAYER MATERIALS

In laminated glass, interlayer materials are utilized to connect the glass panes together. Polyvinyl butyral (PVB), polyester, ethyl vinyl acetate (EVA), resins, ionoplast, and intumescent are examples of interlayer materials. This can be a single layer or multiple layers that operate as an adhesive between glass panes to improve the performance of the finished glass assembly, such as composite action, impact resistance, solar control, acoustic insulation, and so on. Gaskets and setting blocks are among the glazing accessories.

Gasket: A gasket is a type of glazing accessory that can be used with a variety of different contact materials. Durability, compatibility, strength, and ductility have all been addressed in its application. Figure 2.28 shows an example of a typical gasket.

Black heat cured silicone rubber is used for glazing gaskets, sealant backers within glazing pockets, and continuous glass spacer pads for structural sealants.

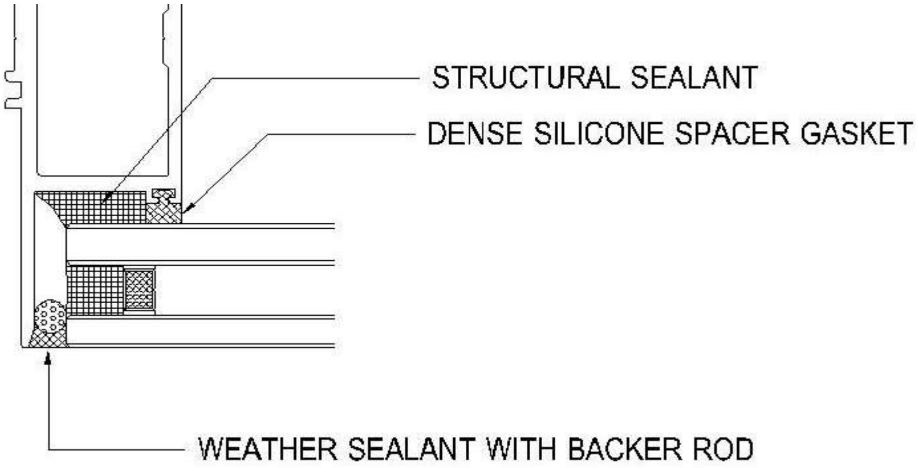


Figure 2.25: Typical mullion (structural sealant) (BDHK, 2018)

Setting Block: In the frame members, the setting block is firmly and permanently installed. Setting blocks could be located at the glass quarter points, equidistant from the glass centerline. Finite element analysis is utilized to check the induced glass stresses in various

`

glass supporting situations, such as bolting and point fittings. Setting block positions are depicted in Figure 2.29 below.

.

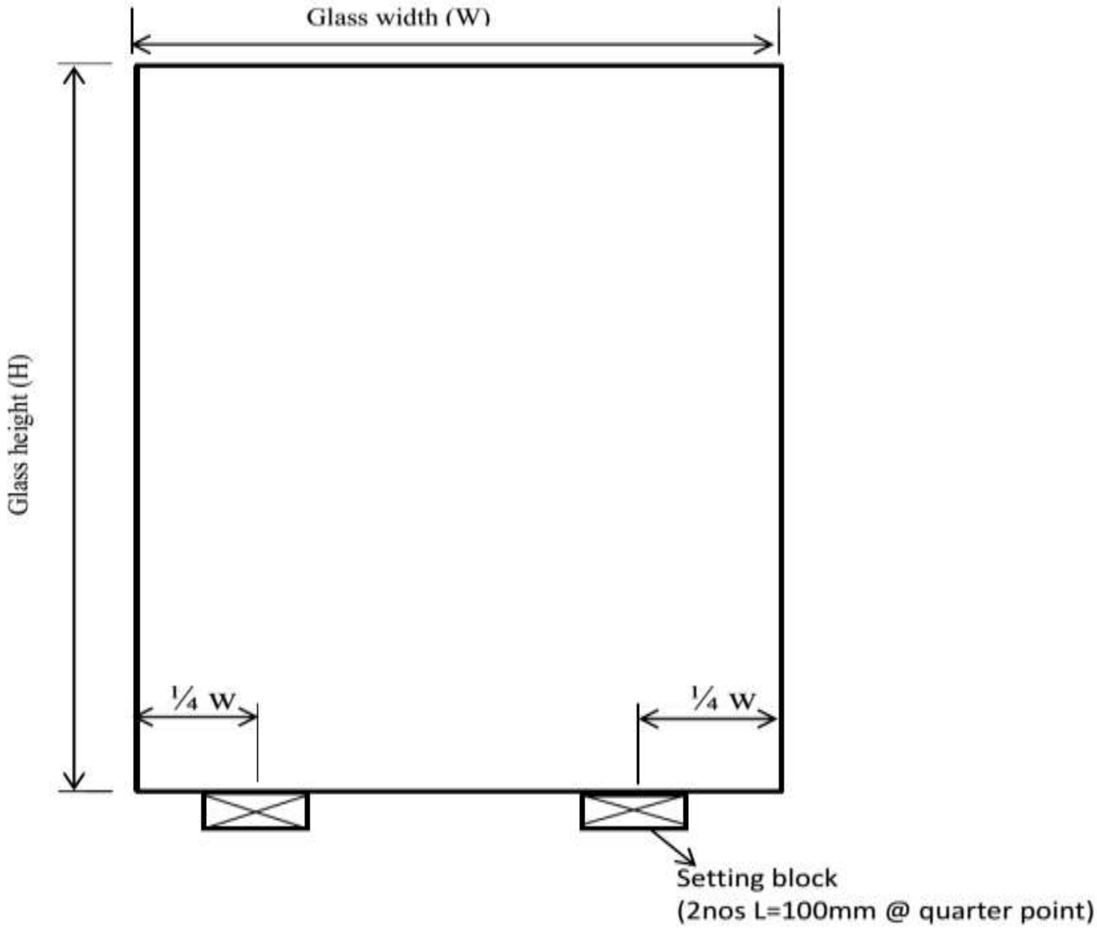


Figure 2.26: Typical location of setting blocks (BDHK, 2018)

`

CHAPTER THREE

3. METHODOLOGY

3.1. FAÇADE DETAIL FOR WIND LOAD

The study started with a review of previous literature on wind load façade details. The goal of this thesis is to show how to construct facades for both in-plane and out-of-plane wind loads. Literature papers on façade details can be found in academic publications, façade manuals, unpublished theses, conference papers, and expert pieces.

Glass façade systems are designed with visual consideration, weather protection, and structural evaluation in mind. Weatherproofing controls air leakage, vapor diffusion, heat loss and gain, and rain water, while visual inspection evaluates the façade's overall aesthetics. The façade's structural design manages both in-plane and out-of-plane pressures and movements.

In-plane design takes into consideration self-weight, thermal expansion, spandrel beam deflection, and in-plane building movements due to wind loads. The glass façade system's spandrel beam is designed to deflect as a result of gravity floor loading and lateral building movement caused by wind loads. Thermal movement of mullions, transoms, and glass panels is also considered to ensure that there is enough space between adjoining panels to allow for movement.

The out-of-plane design takes into account wind loads on the glass panel, mullion, transom, and structural support frames. The most major out-of-plane load is wind. High-wind resistance is integrated into all glass panels, mullions, and transoms.

As a result, the optimum solutions for wind load resistance are structural sealant bite and limit state glass design.

`

The architect usually specifies the size and profile of the glass façade systems, while façade engineers handle the structural design. This thesis determines the details of a glass façade for wind load.

The following steps were taken in order to accomplish the thesis's goal:

1. Structural sealant bite for glazing
2. Limit state design of glass panel
3. Analysis of glass pane using finite element
4. Case study

3.2. STRUCTURAL SEALANT FOR GLAZING

To connect a glass pane to a metal frame or another glass pane, structural sealant is commonly used. The glazing system and the supporting structural frame should be compatible with the structural sealant.

The permissible design strength of Dow corning, a typical form of structural sealant, under short-term and medium-term loads is 138 kPa, according to the Hong Kong code of practice (BDHK, 2018) for structural glass.

The bite of the structural sealant should be at least 6 mm. To prevent tearing during thermal movement, a sufficient sealant thickness should be given.

Risks to building occupants and pedestrians, long-term durability, degree of redundancy, nature of applied loads, and quality control during fabrication and erection are all factors that affect the performance of a structural sealant.

`

The façade system or glass element with structural sealant glazing application must be constructed to prevent the glass pane from falling out if the structural sealant bond fails. Retaining mechanisms for such structural sealant glazing, such as feature capping, angle, bracket, or insert, shall be designed and constructed at the top and bottom of the glass pane for the additional purpose of preventing dislocation or falling in the event of structural sealant bond failure. Setting blocks support the weight of the glass panes mechanically.

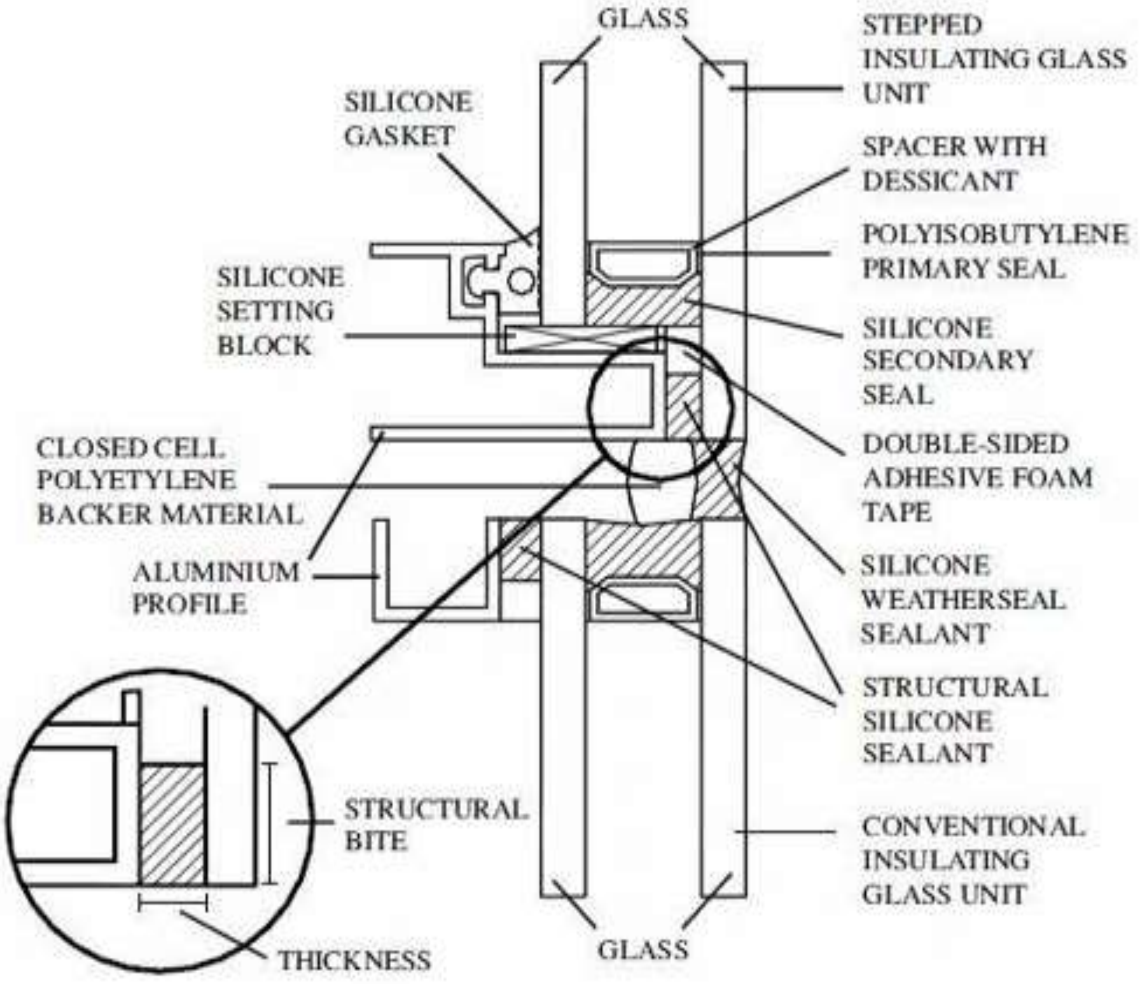


Figure 3.1:Typical Structural Glazing Detail

`

The shorter span of the rectangular glass pane and the design wind load are the governing variables that determine the structural sealant bite requirement for a four-sided structural sealant support. The following equation should be used to determine the minimum structural sealant bite (bi) for wind load and glass dimension.

$$b_i = \frac{0.5 \times p \times L_S}{p_b} \qquad 4.1$$

Where

b_i = minimum structural sealant bite (mm)

L_s = length of shorter span of rectangular glass pane (mm)

P = design wind pressure (kPa) for allowable stress design

P_b= permissible design bond strength (kPa)

For two-sided, three-sided, or structural glazing with irregular glass panes, the structural sealant bite is assessed based on the load distribution on the glass pane.

The glass panes are designed simple supported on a supporting frame.

3.3. LIMIT STATE DESIGNS

The functional limits of strength, stability, and serviceability of both structural elements and the structure as a whole are considered in limit state design. The state beyond the limit state is defined as when the structure no longer meets the necessary design criteria.

According to the Hong Kong Building Department's 2018 Code of Practice for Structural Use of Glass, limit state design is based on the requirement that the structure's "Resistance" exceed the "Load Effects" for all potential modes of failure, taking into account uncertainties in load effects, variability in resistance, and material properties.

Resistance $\geq$ load effects 4.2

`

Load effects are determined using standard structural analysis methods for axial, bending, shear, and torsion in structural members and components, which are then multiplied by a partial load factor (γ_f) to obtain an upper bound estimate of load effects. The resistance effects are determined by the material's normal strength, member shape, and material properties.

Divide the material strength by a partial material factor (γ_m) to produce a lower bound estimate for material properties. This will cover material strength variability, member dimensions variability, and product variability. According to the code, the limit states might be either the ultimate limit state or the serviceability limit state. Glass buildings or elements are designed with limit states in consideration, beyond which they would become unfit for their original purpose.

For ultimate and serviceability limit states, appropriate partial factors are used to provide adequate degrees of reliability. The safety of the whole or portion of the structure is concerned with ultimate limit states, whereas serviceability limit states correspond to the limits beyond which stated service standards are no longer met.

Apart from the partial material factor(γ_m), every design must also account for a partial load factor(γ_f) that covers the loads and variations of expected structural behavior. The values assigned to γ_f are determined by the load type and load combination. The partial load factor is multiplied by the typical loads to determine a structure's ultimate strength and stability.

The out-of-plane design takes into account wind loads on the glass panel, mullion, transom, and structural support frames. The most important out-of-plane load is wind. Glass panels, mullions, and transoms are all designed to withstand critical wind pressure.

`

3.3.1. ULTIMATE LIMIT STATE

In the face of failure, the ultimate limit state describes the strength and stability of structures and structural elements.

a. Strength and Stability

The resistance or capacity of the glass pane must be greater than or equal to the load effects for a satisfactory design of an element at the ultimate limit state. By reducing the ultimate design strength of glass by a partial material factor, the ultimate design resistance of a glass pane is determined. The ultimate design loads are calculated by multiplying the characteristic loads and partial load factors.

b. Progressive Collapse

Glass structures are planned and designed to be resistant to disproportionate collapse, such that damage or failure of a single glass element or small region of a structure does not result in the progressive collapse of a major part of the structure. The breakdown of a glass column, for example, may result in the failure of a glass beam and a glass floor.

To reduce the possibility of localized damage leading to the collapse of a major part of the structure, additional measures and particular care are taken to improve structural integrity and robustness.

The characteristic loads (Q_{char}) are multiplied by a partial load factor (γ_f) to get the ultimate design loads (Q_{ult}):

$$Q_{ult} = \gamma_f Q_{char} \qquad 4.3$$

Design load effects (S_{ult}) have been obtained from the ultimate design loads:

$$S_{ult} = f(effect\ of\ Q_{ult}) \qquad 4.4$$

`

Ultimate design resistance *R_{ult}* is a function of the characteristic or specified material strengths divided by a partial material factor (γ_m) to allow for manufacturing tolerances, variations of material strengths (p_u) and product variability from their characteristic values given in Table 2.3; and multiplied with the strength reduction factor (γ_d) given in Table 2.4 and the glass surface treatment reduction factor (γ_s) given in Table 2.5.

For glass: $R_{ult} = f\left(\frac{\gamma_d \gamma_s p_u}{\gamma_m}\right)$ 4.5

The design resistance R_{ult} must be greater than or equal to the design load effects S_{ult} when designing a structural member at ultimate limit states.

$$R_{ult} \geq S_{ult} \tag{4.6}$$

Partial Load Factors: The partial load factor (γ_f) allows for variations in loads from their characteristic values, as well as the reduced probability that multiple loads acting together will achieve their characteristic values at the same time, as well as calculation errors and structural behavior variations. Below are some load factors and their combinations.

Load Factors and Combinations: The following are the most important load combinations:

- Load combination 1 are: Dead load, imposed load, earth, water and temperature loads
- Load combination 2 are: Dead load, wind load, earth, water and temperature loads
- Load combination 3 are: Dead load, imposed load, wind load, earth, water and temperature loads

Table 3.1 shows the load factors and their combinations for strength and stability under standard design conditions.

`

Table3.1:Partial load factors(γ_f) for load combinations under normal design conditions (BDHK, 2018)

Load combination		**Load type**						
		Dead		**Imposed**		**Earth and water pressure**	**Wind**	**Temperature**
		Adverse	Beneficial	Adverse	Beneficial			
1	Dead, imposed, earth, water and temperature	1.4	1.0	1.6	0	1.4	-	1.2
2	Dead, wind, earth, water and temperature	1.4	1.0	-	-	1.4	1.4	1.2
3	Dead, imposed, wind, earth, Water and temperature	1.2	1.0	1.2	0	1.2	1.2	1.2

Notes:

- Where the action of the earth or water pressure is beneficial, the partial load factor should not exceed 1.0. The value should be taken such that multiplied by the design earth or water pressure equals the actual earth or water pressure.
- All partial load factors for adverse conditions are taken as 1.0 for serviceability limit states.

Partial Material Factors: For glass, the partial material factor on properties such as material strength and modulus of elasticity is taken as 1.0.

Design of Glass Pane Thickness: For a four-sided simply supported glass pane with an aspect ratio (b/a) less than 5, the minimum required glass thickness (t) should not be less than the minimum of t_1 and t_2, as shown below.

$$t_1 = 4.87a^{0.965}b^{0.22}\left(\frac{R}{c}\right)^{0.545} \qquad 4.\ 7$$

`

$$t_2 = 2.33(ab)^{0.665}\left(\frac{R}{c}\right)^{0.87} - 1.62\left(\frac{a}{b}\right) + 1.2 \tag{4.8}$$

The glass thickness (t) should not be less than t_3 for aspect ratios equal to or greater than 5, as given in Eq (3.11) below:

$$t_3 = 6.2a^{1.15}\left(\frac{R}{c}\right)^{0.5} \tag{4. 9}$$

Where

a = length of shorter side of glass pane (m)

b= length of the longer side of glass pane (m)

R= factor designed pressure on individual glass pane (kPa)

=γ_f x design pressure

c = strength coefficient ($c = c_1 \times \gamma_d \times \gamma_s$)

Where

$c_1 -$ Glass type (heat treatment)

= 1.0 for annealed glass

= 2.0 for heat strengthened glass

=4.0 for tempered glass

$\gamma_d -$ load duration factor given in table 2.4

$\gamma_s -$ glass surface treatment reduction factor given in table 2.5

The required glass thickness is calculated using Equations 4.7, 4.8, and 4.9, which take into consideration different glass types, load duration, and glass surface treatment. Only four-sided, simply-supported glass panes are subjected to these equations.

`

3.3.2. SERVICEABILITY LIMIT STATE

Under serviceability design loads, the serviceability limit state considers service requirements for a structure or structural elements. In the serviceability limit state, for example, deflection, human-induced vibration, earthquakes, and wind-induced oscillation are all taken into account.

For a satisfactory design of an element at serviceability limit state, the serviceability design resistance must be greater than or equal to those load effects.

Deflection: The deflection and deformation of the structure or any of its components should not have an unfavorable effect on its efficiency or performance. The degree of movement governed by other connected elements is compatible with deflection.

The structural and serviceability performance of a structural system should not be damaged by glass pane deflection in general. The deflection of a glass pane is calculated using the finite element method, which allows for large deflection effects when necessary, or using the equations below for rectangular glass panes.

Four- side simply supported: $\delta = t^{r_0+r_1x+r_2x^2}$

In which, $x = ln\left[ln\frac{p[ab]^2}{Et^4}\right]$

4.10

Two-side simply supported: $\delta = \frac{5\,pa^4}{32Et^3}$

Where

δ = deflection at center (mm)

a = shorter side of the glass pane (mm) or loaded span in the case of two side simply supported (mm)

b = longer side of the glass pane (mm)

`

t = minimum thickness of the glass pane (mm)

p = design pressure for each glass pane (kPa)

E = modulus of elasticity of the glass pane (kPa)

$$r_o = 0.553 - 3.83\left(\frac{b}{a}\right) + 1.11\left(\frac{b}{a}\right)^2 - 0.0969\left(\frac{b}{a}\right)^3$$

$$r_1 = -2.29 + 5.83\left(\frac{b}{a}\right) - 2.17\left(\frac{b}{a}\right)^2 + 0.2067\left(\frac{b}{a}\right)^3$$

$$r_2 = 1.485 - 1.908\left(\frac{b}{a}\right) + 0.815\left(\frac{b}{a}\right)^2 - 0.0822\left(\frac{b}{a}\right)^3$$

The deflection limit (δ_{limit}) of glass pane should be taken as follows:

Four-side simply supported: (δ_{limit}) = 1⁄60 of the short span

Three-side simply supported: (δ_{limit}) = min. [b⁄60, a⁄30], (see Figure 3.2)

Two-side simply supported: (δ_{limit}) = 1⁄60 of the loaded span

Cantilever: (δ_{limit}) = 1⁄30 of the span

Point supported: (δ_{limit}) = 1⁄60 of the longer span between supports

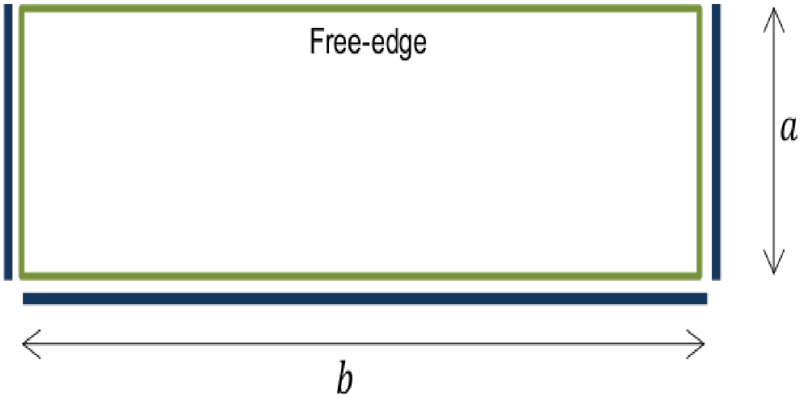


Figure 3.2: Dimensions of glass for three-side supported case (BDHK, 2018)

`

For spans less than 7.2 m, the limit of deflection for structural members is the smaller of 1/180 of the span or 20 mm.

The deflection limit of a member is 1/360 of the span for spans higher than 7.2 m.

The deflection limit for the cantilever member is the smaller of 1/90 of the span or 20 mm.

Vibration: To prevent excessive oscillation caused by the dynamic effects of humans and other forces, structural analysis should be used to determine the natural frequencies of vibration of glass buildings.

Under applied loads, the serviceability limit state considers service requirements for a structure or structural elements. In the case of serviceability design, the partial load factor for all load categories has been set at 1.0.

Durability: For its durability, a glass structural system requires unique design considerations such as quality control and testing. Boil tests and weathering tests, for instance, should be required to be carried out while taking local conditions into account.

3.4. FINITE ELEMENT METHOD

The glass pane deflection and stress for a given thickness will be analyzed using finite element analysis. The behavior of a glass panel was investigated using the Lisa 8.0 finite element analysis method. Lisa does not have a unit system, so all quantities must be measured in the same way.

3.5. CASE STUDY

As an example of a unitized framed glass façade system for this thesis, Figure 3.1 illustrates a 9.8m x 3.6m façade frame grid with six internal 1500mm wide panels and two end panels 800mm wide to cover the external columns. Glass façade systems must meet a variety of out-of-plane and in-plane design criteria to perform satisfactorily. In general, the façade is designed using the general pressure coefficients for the normal design wind pressure, and thicker glass panels may be required at the corners to meet the greater pressure associated with vortex shedding. Some engineers design all façade panels conservatively based on the greater corner wind pressure.

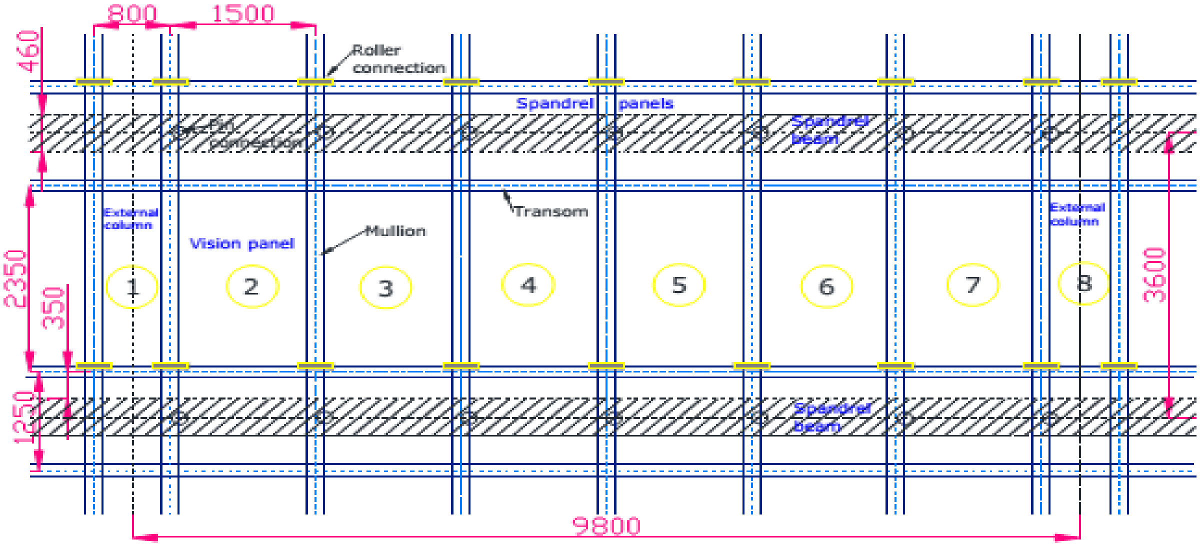


Figure 3.3:Typical layout of unitized framed glass façade system for façade grid

`

Table 3.2:The mechanical properties of glass and associated strength coefficients (c1)

Types of glass	Annealed glass	Heat strength glass	Tempered glass
Elastic modulus (E)	70,000N/mm^2		
Density(ρ)	2650kg/m^3		
Strength coefficient ($c= c_1 \times \gamma_d \times \gamma_s$) So, value of c_1 is	1	2	4
Sealant design strength	138kPa		

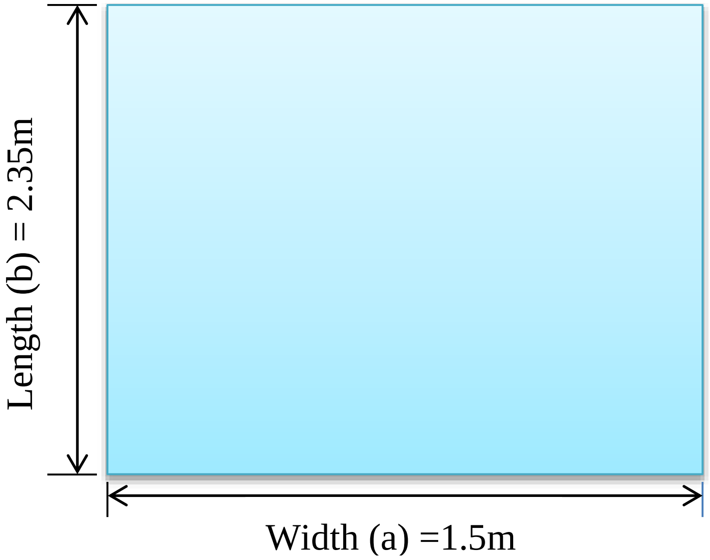


Figure 3.4: Geometry of glass pane

Wind pressure calculation;

The basic wind pressure is 1500 meters above sea level, and the reference wind velocity is 22 m/sec for a maximum building height of 20 meters. The wind pressure is calculated as follows according to EBCS 1 on wind effects.

$$p_z = \frac{\rho}{2} {v_{ref}}^2 \qquad 4.\ 11$$

Where

ρ =1.00kg/m^3

`

$V_{ref} = C_{DIR} \text{ x } C_{TEM} \text{ x } C_{ALT} V_{ref,0}$ = 1 x 1 x 1 x 22 m/sec = 22 m/sec

$$p_z = \frac{\rho}{2} {v_{ref}}^2 = \frac{1kg/m^3}{2} (22\, m/\text{sec})^2 = 242\, N/m^2 = 242\, Pa = 0.242kPa$$

Basic wind pressure (P_z) = 0.242 kPa

For edge zone of building,

Pressure coefficients, Cp = -1.4 (suction) and +0.33 (pressure)

So, design wind pressure (p) = -1.4 x 0.242 kPa = -0.34kPa (suction)

And = 0.33*0.242kPa = +0.08kPa (pressure)

Therefore; the total design wind pressure (p) = 0.34 kPa

Once again, the factorized design wind pressure (R) = γ_f x design pressure

= 1.4 x 0.34 kPa

= 0.476 kPa

AR= longer side /shorter side = 2350/1500= 1.57 which is less than 5,

Four-side simply supported glass pane with an aspect ratio (b/a) less than 5, the minimum required glass thickness should not be less than the minimum of t_1 and t_2.

$$t_1 = 4.87a^{0.965}b^{0.22}\left(\frac{R}{c}\right)^{0.545}$$

$$t_2 = 2.33(ab)^{0.665}\left(\frac{R}{c}\right)^{0.87} - 1.62\left(\frac{a}{b}\right) + 1.2$$

Where

a = length of shorter side of glass pane (m) =1.5m

b= length of the longer side of glass pane (m) =2.35m

R= factor designed pressure on individual glass pane (kPa) = $1.4 \times 0.34 = 0.476\ kPa$

`

c = strength coefficient ($c = c_1 \times \gamma_d \times \gamma_s$)

Where

c_1 − Glass type

= 1.0 for annealed glass

= 2.0 for heat strengthened glass

=4.0 for tempered glass

γ_d − load duration factor given in table 2.4

γ_s − glass surface treatment reduction factor given in table 2.5

Deflection for a rectangular glass pane;

Four- side simply supported: $\delta = t^{r_0 + r_1 x + r_2 x^2}$

In which, $x = ln\left[ln\frac{p[ab]^2}{Et^4}\right]$

Two-side simply supported: $\delta = \frac{5\,pa^4}{32Et^3}$

Where

δ = center deflection (mm)

a = length of shorter side of glass pane (mm) =1500mm

Or loaded span in two sides simply supported case (mm)

b = length of longer side of glass pane (mm) = 2350mm

t = minimum glass pane thickness (mm) = 4.78mm calculated

p = design pressure on individual glass pane (kPa) =0.34 kPa

E = modulus of elasticity of glass pane (kPa) =70000000 kPa

`

$$r_o = 0.553 - 3.83\left(\frac{b}{a}\right) + 1.11\left(\frac{b}{a}\right)^2 - 0.0969\left(\frac{b}{a}\right)^3$$

$$r_1 = -2.29 + 5.83\left(\frac{b}{a}\right) - 2.17\left(\frac{b}{a}\right)^2 + 0.2067\left(\frac{b}{a}\right)^3$$

$$r_2 = 1.485 - 1.908\left(\frac{b}{a}\right) + 0.815\left(\frac{b}{a}\right)^2 - 0.0822\left(\frac{b}{a}\right)^3$$

Using finite element method;

Loading data summary:

- Loading pressure = 0.34kPa=340Pa
- Glass thickness = 4mm= 0.004m
- Tempered glass size = 1500mm x 2350mm = 1.5 m x 2.35 m
- Glass with 4 sides supported by mullions and transoms

`

CHAPTER FOUR

4. RESULT AND DISCUSION

The results and discussions of the methods of structural sealant bite, limit state designs, and finite element on the case-study are presented in this chapter.

4.1. RESULTS

4.1.1. STRUCTURAL SEALANT BITE FOR GLAZING

The structural bite requirement is directly proportional the wind load on the building and the dimension of the glass. The higher the wind load and the larger the dimensions of the glass are, the greater the amount of structural bite required.

$$\mathrm{b_i} = \frac{0.5 \times \mathrm{p} \times \mathrm{L_s}}{\mathrm{p_b}}$$

P = 0.34kPa; P_b = 138kPa and shorter span (L_s) = 1500mm

$$\mathrm{b_i} = \frac{0.5 \times 0.34\mathrm{kPa} \times 1500mm}{138kPa}$$

$$\mathbf{b_i} = \mathbf{0.0012} \times \mathbf{L_S}$$

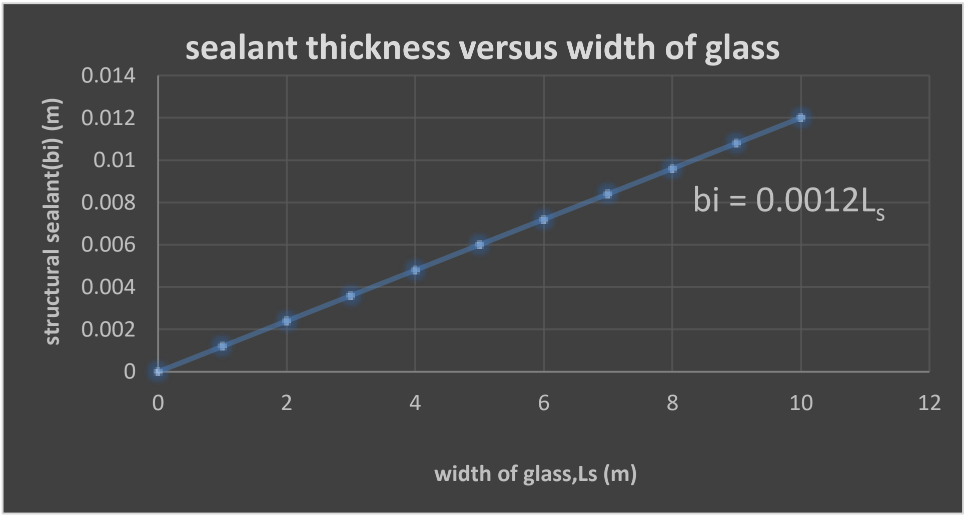


Figure 4.1:Graph for Structural Sealant (b_i) versus Width of Glass Pane (L_s)

`

4.1.2. LIMIT STATE DESIGN

Using ultimate and serviceability limit states;

For Annealed glass type (c_1=1)

$$c = c_1 \times \gamma_d \times \gamma_s = 1 \times 1 \times 1 = 1$$

So $t_1 = 4.87 \times 1.5^{0.965} \times 2.35^{0.22} \left(\frac{0.476}{1}\right)^{0.545}$=**5.80mm**

$t_2 = 2.33 \times (1.5 \times 2.35)^{0.665} \times \left(\frac{0.476}{1}\right)^{0.87} - 1.62 \left(\frac{1.5}{2.35}\right) + 1.2$=**3.00mm**< 5.80mm;

The required thickness is t_1; which is 6mm.

Using the serviceability limit state, check the deflection for the design thickness.

For four- side simply supported:

$$\delta = t^{r_0+r_1x+r_2x^2} \text{ And, } x = ln\left[ln\frac{p[ab]^2}{Et^4}\right]$$

$$x = ln\left[ln\frac{0.34[1500\times2350]^2}{70000000\times6^4}\right]=\mathbf{1.350}$$

$$r_o = 0.553 - 3.83\left(\frac{2350}{1500}\right) + 1.11\left(\frac{2350}{1500}\right)^2 - 0.0969\left(\frac{2350}{1500}\right)^3 = \mathbf{-3.096}$$

$$r_1 = -2.29 + 5.83\left(\frac{2350}{1500}\right) - 2.17\left(\frac{2350}{1500}\right)^2 + 0.2067\left(\frac{2350}{1500}\right)^3=\mathbf{2.312}$$

$$r_2 = 1.485 - 1.908\left(\frac{2350}{1500}\right) + 0.815\left(\frac{2350}{1500}\right)^2 - 0.0822\left(\frac{2350}{1500}\right)^3=\mathbf{0.180}$$

So, $\delta = t^{r_0+r_1x+r_2x^2} = 6^{-3.096+2.312\times1.350+0.180\times1.350^2}$=**1.88mm**

Two-side simply supported: $$\delta = \frac{5\text{ pa}^4}{32\text{Et}^3}$$

$$\delta = \frac{5 \times 0.34 \times 1500^4}{32 \times 70000000 \times 6^3} = \mathbf{17.787}\boldsymbol{mm}$$

`

For Heat strengthen glass type (c1= 2)

$$c = c_1 \times \gamma_d \times \gamma_s = 2 \times 1 \times 1 = 2$$

So, $t_1 = 4.87 \times 1.5^{0.965} 2.35^{0.22} \left(\frac{0.476}{2}\right)^{0.545}$=**3.975mm**

$t_2 = 2.33(1.5 \times 2.35)^{0.665} \left(\frac{0.476}{2}\right)^{0.87} - 1.62 \left(\frac{1.5}{2.35}\right) + 1.2$=**1.711mm**< 3.975mm;

The required thickness is t_1; which is 4mm.

Using the serviceability limit state, check the deflection for the design thickness.

Four- side simply supported:

$\delta = t^{r_0 + r_1 x + r_2 x^2}$ And, $x = ln\left[ln \frac{p[ab]^2}{Et^4}\right]$

$x = ln\left[ln \frac{0.34[1500 \times 2350]^2}{70000000 \times 4^4}\right]$=**1.700**

$r_o = 0.553 - 3.83\left(\frac{2350}{1500}\right) + 1.11\left(\frac{2350}{1500}\right)^2 - 0.0969\left(\frac{2350}{1500}\right)^3$ = **-3.096**

$r_1 = -2.29 + 5.83\left(\frac{2350}{1500}\right) - 2.17\left(\frac{2350}{1500}\right)^2 + 0.2067\left(\frac{2350}{1500}\right)^3$=**2.312**

$r_2 = 1.485 - 1.908\left(\frac{2350}{1500}\right) + 0.815\left(\frac{2350}{1500}\right)^2 - 0.0822\left(\frac{2350}{1500}\right)^3$=**0.180**

So, $\delta = t^{r_0 + r_1 x + r_2 x^2} = 4^{-3.096 + 2.312 \times 1.700 + 0.180 \times 1.700^2}$=**6.54mm**

Two-side simply supported: $\delta = \frac{5\,pa^4}{32Et^3}$

$$\delta = \frac{5 \times 0.34 \times 1500^4}{32 \times 70000000 \times 4^3} = \mathbf{60.03mm}$$

For Tempered glass type (c1=4)

$$c = c_1 \times \gamma_d \times \gamma_s = 4 \times 1 \times 1 = 4$$

`

So,

$$t_1 = 4.87 \times 1.8^{0.965} 2.4^{0.22} \left(\frac{0.476}{4}\right)^{0.545}$$ =**3.26mm**

$$t_2 = 2.33(1.5 \times 2.35)^{0.665} \left(\frac{0.476}{4}\right)^{0.87} - 1.62\left(\frac{1.5}{2.35}\right) + 1.2$$ =**0.95mm**< 3.26mm;

The required thickness is t_1; which is 4mm.

Using the serviceability limit state, check the deflection for the design thickness.

Four- side simply supported:

$$\delta = t^{r_0 + r_1 x + r_2 x^2}$$ And, $$x = ln\left[ln \frac{p[ab]^2}{Et^4}\right]$$

$$x = ln\left[ln \frac{0.34[1500 \times 2350]^2}{70000000 \times 4^4}\right]$$=**1.700**

$$r_o = 0.553 - 3.83\left(\frac{2350}{1500}\right) + 1.11\left(\frac{2350}{1500}\right)^2 - 0.0969\left(\frac{2350}{1500}\right)^3$$ = **-3.096**

$$r_1 = -2.29 + 5.83\left(\frac{2350}{1500}\right) - 2.17\left(\frac{2350}{1500}\right)^2 + 0.2067\left(\frac{2350}{1500}\right)^3$$=**2.312**

$$r_2 = 1.485 - 1.908\left(\frac{2350}{1500}\right) + 0.815\left(\frac{2350}{1500}\right)^2 - 0.0822\left(\frac{2350}{1500}\right)^3$$=**0.180**

So, $\delta = t^{r_0 + r_1 x + r_2 x^2} = 4^{-3.096 + 2.312 \times 1.700 + 0.180 \times 1.700^2}$=**6.54mm**

Two-side simply supported: $$\delta = \frac{5\,pa^4}{32Et^3}$$

$$\delta = \frac{5 \times 0.34 \times 1500^4}{32 \times 70000000 \times 4^3} = \boldsymbol{60.03mm}$$

`

4.1.3. Finite Element Method

The results of the finite element method for deflection and stress for a given design thickness of glass and wind pressure.

I. Loading diagram

Loading data summary:

- Loading pressure = 0.34kPa=340Pa
- Glass thickness = 4mm= 0.004m
- Tempered glass size = 1500mm x 2350mm = 1.5 m x 2.35 m
- Glass with 4 sides supported by mullions and transoms

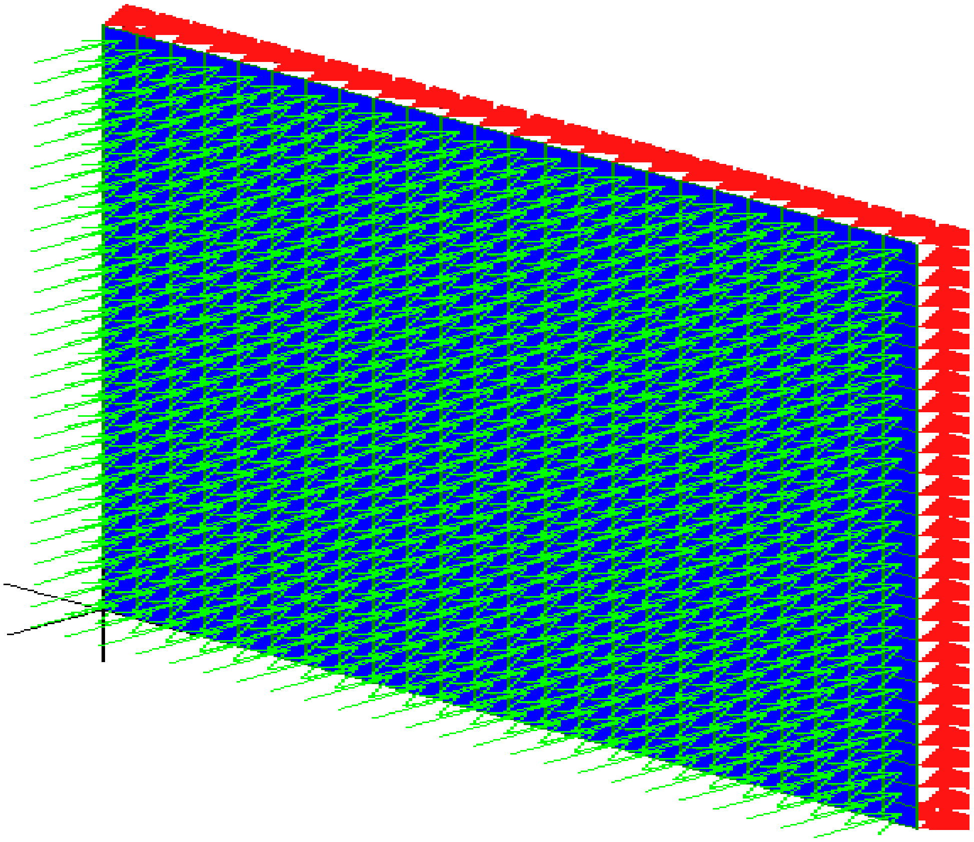


Figure 4.2: Load Diagram of vision glass (Lisa 8)

`

II. Deflection diagram:

Plate deflection in (m)

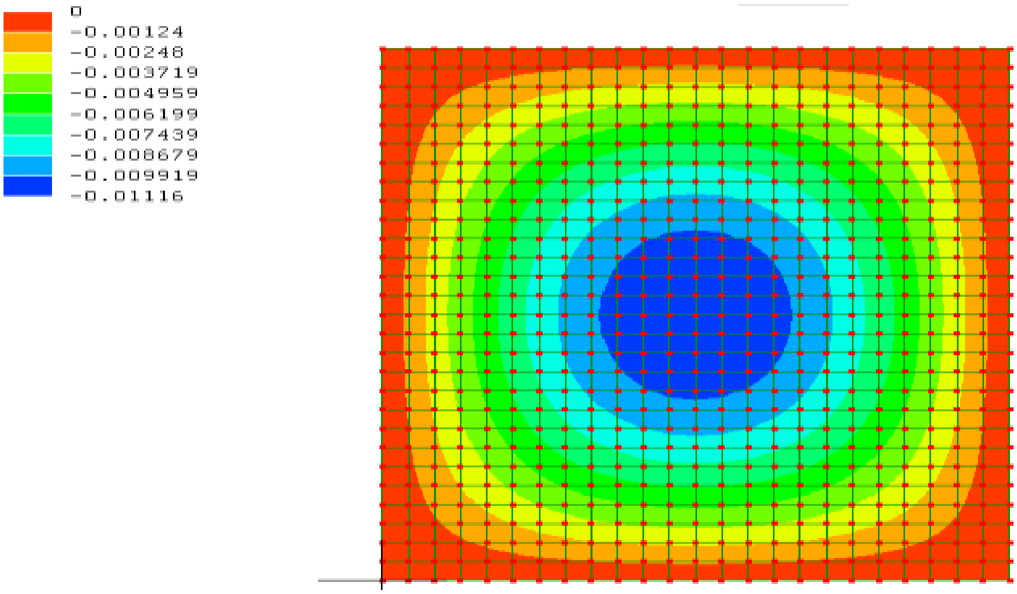


Figure 4.3: Deflection Diagram of vision glass (Lisa 8.0)

III. Stress diagram:

Plate deflection in (pa)

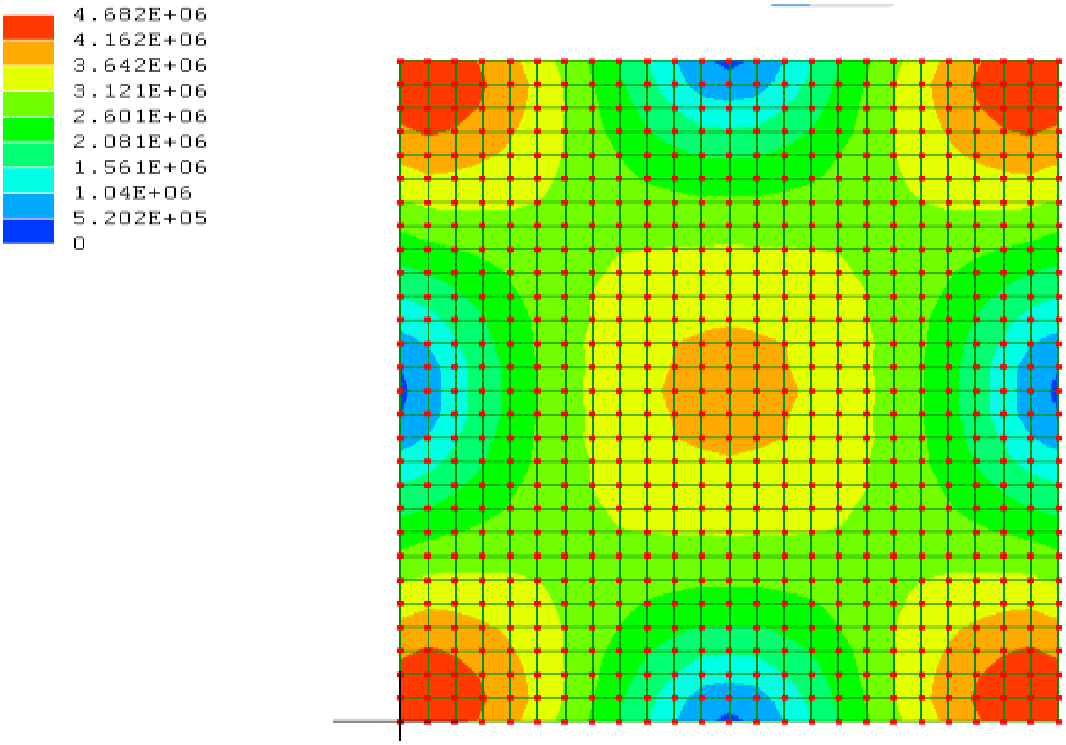


Figure 4.4:Stress Diagram of vision glass (Lisa 8.0)

`

4.2. DISCUSSION

The structural bite requirement is directly proportional to the wind load on the building and the glass dimension. The higher the wind pressure and the larger the glass size, the greater the structural bite required.

For Annealed glass type (c_1=1)

For a given load, the required glass pane thickness is 6mm.

The deflection limit (δ_{limit}) of glass pane should be taken as follows

Four-side simply supported: (δ_{limit}) = $^1/_{60}$ of the short span

(δ_{limit}) = 1⁄60 of the short span =$\left(\frac{1}{60}\right) \times 1500mm = \mathbf{25mm} > 1.88mm$ …….**accepted**

Two-side simply supported: (δ_{limit}) = $^1/_{60}$ of the loaded span

(δ_{limit}) = $^1/_{60}$ of the loaded span=$\left(\frac{1}{60}\right) \times 2350mm = \mathbf{39mm} > 17.787mm$…….**accepted**

For cost-effectiveness, two sides simply supported are sufficient to support the specified load.

For Heat strengthen glass type (c_1= 2)

For a given load, the required glass pane thickness is 4mm.

The deflection limit (δ_{limit}) of glass pane should be taken as follows

Four-side simply supported: (δ_{limit}) = $^1/_{60}$ of the short span

(δ_{limit}) = $^1/_{60}$ of the short span =$\left(\frac{1}{60}\right) \times 1500mm = \mathbf{25mm} > 6.54mm$ ……**..accepted!**

Two-side simply supported: (δ_{limit}) = $^1/_{60}$ of the loaded span

(δ_{limit}) = $^1/_{60}$ of the loaded span=$\left(\frac{1}{60}\right) \times 2350mm = \mathbf{39mm} < 60.03mm$. **Not accepted!**

For a given load, it is preferable to have four sides simply supported.

`

For Tempered glass type (c_1=4)

For a given load, the required glass pane thickness is 4mm.

The deflection limit (δ_{limit}) of glass pane should be taken as follows

Four-side simply supported: (δ_{limit}) = ${}^{1}/{}_{60}$ of the short span

(δ_{limit}) = ${}^{1}/{}_{60}$ of the short span =$\left(\frac{1}{60}\right) \times 1500mm = \boldsymbol{25mm} > 6.54mm$ …….**accepted!**

Two-side simply supported: (δ_{limit}) = ${}^{1}/{}_{60}$ of the loaded span

(δ_{limit}) = ${}^{1}/{}_{60}$ of the loaded span=$\left(\frac{1}{60}\right) \times 2350mm = \boldsymbol{39mm} <$ 60.03mm.**Not accepted**!

For a given load, it is preferable to have four sides simply supported.

According to Hong Kong Building Department rules, the deflection limit for glass is Span/60 or 25mm, whichever is smaller.

The maximum deflection, as indicated in figure 3.5, is 11.16mm, which is less than 25mm. As a result, the outcome is acceptable.

The maximum deflection is found near the glass's centroid, according to the contour deflection diagram. The result was acceptable, with the highest defection at the centroid, because the glass was supported by four sides.

According to AS 1288, tempered glass has a stress limit of 49MPa.

According to the results shown in figure 3.6, the maximum stress is 4.6MPa, which is less than 49MPa. As a result, the outcome is acceptable.

The maximum stress is located at the four corners of the panel, according to the contour stress diagram. The glass was also deformed inward from the centroid when normal pressure force was applied to the glass because the panel was supported by four sides.

`

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The main variables that affect the structural bite requirement are the short span dimension of glass and the design wind load that the structural glazing system must accommodate.

The theoretical analysis of the design of glass thickness is governed by factors such as glass size, factored design wind pressure, and glass strength factor.

Glass deflection and stress behavior were governed by size and wind pressure, according to the results of finite element analysis. The majority of the time, glass breaks for a reason. As a consequence, prior to construction, engineers must analyze the actual condition of the glass.

5.2. RECOMMENDATIONS

The façades are subjected to wind, earthquake, dead, alive, temperature, and other loads. Although the goal of this thesis was to look at the details of a façade for wind loads, future façade researchers should look at the details of a façade for other loads as well.

`

REFERENCE

AAMA (American architectural manufacturers association) (1996), 'curtain wall design guide manual'

AS1288, 2006, Glass in buildings - Selection and installation. Australian Standard, Standards Australia, 1 the Crescent, Homebush, NSW 2140.

AS3600, 2009. Concrete structures. *Australian Standard, Standards Australia, 1 the Crescent, Homebush, NSW 2140.*

ASCE7-10, 2010, Minimum design loads for buildings and other structures. 1801 Alexander Bell Drive, Reston, Virginia 20191-4400: The American Society of civil engineers.

AS1170.4, 2007, Structural design actions, Part 4: Earthquake Actions in Australia. Australian Standard, Standards Australia, 1 The Crescent, Homebush, NSW 2140.

BCA, 2011, Building Code of Australia. Canberra, A.C.T: Australian Building Codes Board.

BDHK (Building Departments of Hong Kong), 2018, Code of Practice for Structural Use of Glass. [Online] Available from: http://www.bd.gov.hk/ [accessed 1st February 2018].

FEMA 356, 2000, Pre standard and Commentary for the Seismic Rehabilitation of Buildings. Washington, D.C.: Federal Emergency Management Agency.

FEMA 440, 2005. Improvement of Nonlinear Static Seismic Analysis Procedures. *Applied Technology Council (ATC-55 Project)*. Redwood

Gerd H, Director pre-construction service. (Personal communication, 14th August 2017).

John, W.and Sons. (2011) *Structural Glass Facades and Enclosure* .john wiley and sons, Inc. Hoboken, New Jersey

Jose, S. (2013) *Analysis and Design of Structural Glass System*. Institutor superior technical university of Lisbon.

Naimeh, K. (2004) *Design Principles for Glass Used Structurally*. Department Of Building Science, Lund University, Sweden.

Pallavi, W.T. & Santosh, D.S. (2015) structural design of a glass façade. *International Journal* of Scientific and Research Publication. [Online] 5(3). Available from: http://www.ijsrp.org.

Rick Quirouette, 1999, 'Glass and Aluminum Curtain Wall Systems'

Sivanerupan, S., Wilson, L. & Gad, F. (2011) Structural analysis and design of glazed curtain wall systems. *Australian Journal of Structural Engineering (AJSE)*, 12, 57-67.

Sur. K., & Tsang, H. (2008) Seismic drift demand and capacity of non-seismically designed concrete building in Hong Kong. *Electronic Journal of Structural Engineering.*

`

Sucuoglu, H. & Vallabhan, C.V.G. (1997) behavior of window glass during earthquakes engineering structures, 19,685-694.

Thomas, H., Roland, K. and Werner, L. (eds) 2004 *Façade Construction Manual* ,Institute For Design And Building Technology, Faculty of Architecture , Chair of Building Technology, Munich Technical University, Germen

Tom castle, SE. (2012) *Designing with Glass Aluminum and Stainless*. [Presented] building industry, 14th December.

WILSON, J. L. & LAM, N. T. K., (2005), Earthquake design of buildings in Australia using velocity and displacement principles. *Australian Journal of Structural Engineering,* 6,103-118.