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Analysis and Design of Curtain Wall Systems for High Rise Buildings

A dissertation submitted by

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ABSTRACT

Façades are the first aesthetical feature of a building that distinguish one building from another. Its distinctive appearance is often the subject of controversial debate. Nowadays, Unitized Curtain Wall system is commonly used for new high-rise buildings, it becomes a major investment in both construction and long-term success of the building. Compared to reinforced concrete structure, unitized curtain wall is new technology in the construction industry. This dissertation will focus on the design and analysis of unitized curtain wall for high-rise building, using finite element and structural analysis programme. The curtain wall systems nowadays, even the simpler types, are far more sophisticate products than their early counterparts, though many of the earliest walls are still performing admirably. More than fifty years of experience and development have eliminated the major difficulties of the pioneering designs, resulting in better products. Beginning with the relatively simple, but innovative concept of the early 1950's, a series of window units and panels jointed and supported by simple framing members. Curtain wall system technology has developed, over the years, into a proliferation of highly engineered design.

The author worked in construction industry for 5 years and working in Façade Consultancy for almost 2 years. I am currently engaging in various key Façade projects in Asia. I have found that some people simply think that curtain wall system is just an assembly of glass, aluminium, steel, screw and sealant. Curtian wall system, apart from its appearance, functions as an external enclosure to protect the building from weather and to achieve pressure-equalization between the outdoor and indoor environment. Its construction is not only an assembly of several components, but an advanced technology with involves sophisticated calculation. In this paper, design concerns of the unitized curtain wall system are also regarded as major issue to discuss.

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CERTIFICATION

I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

Date

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November, 2007

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CHAPTER 1

INTRODUCTION

1.1 Background information on the research project

Façades are the first aesthetical feature of a building that distinguish one building from another. They determine its distinctive appearance and are often the subject of controversial debate.

Fig.1, shows a new shopping and business building developed in Hong Kong, China. The concept of Architect for this building was a gift box with a bufferfly silk ribbon on the top. Even not everyone have this sense, it is true that the distinctive façade is being an attractive topic to everyone.

Fig. 1 – Mega Box at Kowloon Bay, Hong Kong, China (Completed 2007)

Development in façades has made it more functional, providing designers with the flexibility to create high performance solutions, which are visually exciting, both internally and externally.

As an example was shown in Fig. 2, a new commercial building in Hong Kong, which was awarded for Architectural and Environment design. This building was impressed by the sensitive handling of variation in floor plate dimensions which suit different tenant's requirements and sensible incorporation of hi-tech curtain wall and sun-shading devices with provide comfort to the users while maximizing the panoramic harbour view (famous scene in Hong Kong). An overall transparency of the building and a unity of architectural expression are maintained without giving in to stringent statutory control and cutting edge building technology.

Fig.2 – One Peking Road at Tsim Sha Tsui, Hong Kong, China (Completed 2003)

Major advancements in façade technology gives Architects and Specialists the opportunity to vary the appearance of the building envelope, create an integrate grid system with all of their ideas, such as, windows, ventilation elements, aluminum features, etc. while maintaining a high level weather proofing.

Façade works include such important building components as windows wall, curtain wall, cladding panel, etc, that form an integral part of the external envelope of a building. It is, therefore, important to ensure façade structures are properly designed, installed and maintained, to provide an interesting living environment, while maintaining 'green' and safe living environment for the community. In fig.3, it is a scene of one of business city in China. It shows that there are many high rise buildings with façade envelope nowadays.

Fig.3 – Scene of Hong Kong Island in Hong Kong, China (Photo taken in 2007)

The followings are some project photos of Unitized Curtain Wall for high-rise building as example references.

Fig. 4 –170m Height, Bank of China, Hong Kong, China (Completed 1991), which was the tallest building in Hong Kong in 20th Century

Fig. 5 – 290m height, International Commerce Centre, Hong Kong, China (Right hand side, Under progress), which will be the tallest building in Hong Kong.

Fig. 6 – 890m Height, Buji Tower, Dubai (Under progress)

1.2 Aims

The aims of this project are to introduce the Façade Industry and to analyze the curtain wall system for high-rise building with finite element and structural analysis software.

1.3 Structure of Dissertation

Firstly, I will show the development history of curtain wall system. And, point out the advantages of unitized curtain wall system compare with stick and hybrid curtain wall system.

Secondary, I will focus to introduce modern curtain wall system, which is

Unitized Curtain Wall System.

Thirdly, I will show the design of curtain wall system. The major design consideration includes structural integrity, provision for movement and weather tightness.

Finally, using the case study project to analyze curtain wall system by two softwares, i.e. Strand 7 for finite element analysis, and Space Gass for structural analysis.

1.4 Summary

The curtain wall, one of architecture's most provocative metaphors, is surprisingly difficult to pin down with a precise definition. Generally it was thought of as performing the major functions, which is forming a protective enclosure excluding the elements, but with openings for vision and ventilation as required.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will review published research that has investigated the behaviour of Unitized Curtain Wall System. Curtain wall is defined in terms of its functional relationship to the building's structure. It then refers to the cladding, or enclosure, of a building as something both separate from and attached to the building's skeletal framework. Curtain walls are the most abused of building elements being subjected to wind loading, extreme events, building movements, sudden temperature changes, driven rain, atmospheric pollution and corrosion (Hunton & Martin 1987).

Nowadays, curtain wall system is a major investment in both the construction and the long-term success of the building. Curtain wall system is not just a barrier to the external envelope of building, it is crucial to the image and the perception of a building. A good curtain wall design system with excellent performance is essential; otherwise, it will cause large expenditure in future maintenance.

2.2 Theoretical Studies

2.2.1 Finite Element Analysis Studies

Finite element program, STRAND 7 is used to predict the deflection behaviour of glass panel of Unitized Curtain System. Surface stress is plotted for the ease of understanding of nonlinear behavior when the glass undergoes large deformation.

Owing to possible saving in material weight, nonlinear and large deflection plate theory has been commonly used in some western countries like United States and Canada. With the trend of globalization, it appears that Engineers need to equip themselves on various new techniques for enhancing their competitiveness and non-linear analysis and design is considered to be one of these advanced techniques. Glass panel is commonly used in Curtain Wall Systems (So et al. 2006)

Glass plates are widely used as glazing panels in buildings to date and it has a unique and important quality of transparency and acceptable strength (So, Lai and Chan, 2003). Its provision of unobstructed view to the occupants has made it highly competitive against other types of facades. However, the failure of glass panels is common and the direct falling of glass debris onto the street level may also cause casualties. Studies have shown that breakage of glass is due to the concentrated tensile stress on the surface flaw. Due to the difficulty in estimating the density, orientation and location of these flaws in glass panels, the failure probability instead of direct specification of failure load for a glass panel is usually used a reference for safety of glass structures. Generally speaking, the probability of failure (POF) of 8/1000 is acceptable for most purpose. In congested area, the POF should be further reduced. Glass panels are usually fixed to a building as building envelop. Typically the glass is held in place by means of adhesive strength of silicone sealant and/or mechanical fixing.

To evaluate the stress in a glass panel numerically, the classical close-form solution method, the finite difference method and the finite element method can be used. Generally speaking, the classical method solving directly the equilibrium equation using the strong formulation can only be used in some very simple cases. The finite difference method involves less computational work than the finite element method but may be limited to standard or simple plate geometry. For glass panels with odd shape and under complicated boundary conditions such as the edges are not completely or fully restrained along their sides, these methods may be too complex, if not impossible. The finite element method is generally considered to be the most versatile in terms of flexibility.

The discussion of analysis results will be illustrated in the Chapter 5 with my case study.

2.2.2 Structural Analysis Studies

Because structural failure may jeopardized human life, the structural integrity of the wall may be said to be the primary concern in unitized curtain wall system. To sustain structural integrity, curtain wall system must be analysed by structural analysis programme, so that it obtains support but it not subjected to any loading from the building.

The method is based on the actual response of a structure under ultimate or serviceability limit loads and design is completed simultaneously with analysis.

Space Gass is used for my case study as structural analysis programme.

For Unitized Curtain Wall System, Mullion (known as vertical member) and Transom (known as horizontal member) are mostly analyzed by structural analysis programme. Their bahaviour such as deflection and moment can be obtained from analysis results.

In the general practice, four floors of mullion is modeled in the structural analysis programme when calculate typical unitized curtain wall system. Although, more conservative result can be obtained when modeling whole building structural, it will consume a lot of time. From experience, nearly 90% of actual condition result can be obtained from four floors model by structural analysis programme.

Transom, which will suffer two directions load - wind pressure and dead load. Biaxial load analysis of Transom can be generated by structural analysis programme.

The analysis results will be discussed in the Chapter 5 for my case study.

2.3 Design Codes

Currently, Chinese Code contains the only design standard for whole Façade system including Unitized Curtain Wall System. However, some guidance for the design of different component parts of Unitized Curtain Wall System is provided by the European Committee for Standardisation, the ASTM International Standard, Australian Standards and British Standard, they are all commonly used for reference in some countries. The design codes are based on several different theories, which can produce different results, and the assistance provided in terms of application varies significantly.

Some of these design codes were introduced as follow, which were used in my case study refer to Chapter 5

2.3.1 ASTM E1300 (2004) : Standard Practice for Determining Load Resistance of Glass in Buildings

This practice describes procedures to determine the load resistance of specified glass types, including combinations of glass types used in a sealed insulating glass unit, exposed to a uniform lateral load of short or long duration, for a specified probability of breakage.

This practice applies to vertical and sloped glazing in buildings for which the specified deign loads consist of wind load, snow load and self-weight with a total combined magnitude less than or equal to 10kPa. This code includes the analysis for different glass types, such as monolithic, laminated or insulating glass constructions of rectangular shape with continuous lateral support along one, two, three or four edges. This practice has following assumption:

- the supported glass edges for two, three and four sided support conditions are simply supported and free to slip in plane;
- glass supported on two sides acts as a simply supported beam; and
- glass supported on one side acts as a cantilever.

2.3.2 BS 8118 (1991): Structural Use of Aluminium. Code of Practice for Design

For most of construction projects, Mullion and Transom are made of Aluminium Extrusion. BS 8118 part one is used as the design code for all aluminium structures.

This code provides recommendations for deign of the elements of framed, lattice and stiffened plate structures, using wrought aluminium alloy. The design recommendations are for a variety of aluminium alloys suitable for structural use, and apply to a range of structures subjected to normal atmospheric conditions These recommendations for use in unitized curtain wall are included:

- Deflection limit
- Stress limit
- Section classification
- Bearing stress limit

2.3.3 BS 5950 (2000): Structural Use of Steelwork in Building. Code of Practice for Design. Rolled and Welded Section.

Component parts such as bracket, bolt and nut, steel angle etc., which were used for fixing the unitized curtain wall panel, were all made of steel. BS 5950 part one is used as the design code for all steel fixings.

This code gives recommendations for the design of structural steelwork using hot rolled steel sections, flats, plates, in buildings and allied structures not specifically covered by other standards. These recommendations for commonly used in unitized curtain wall are included:

- Deflection limit
- Stress limit
- Bearing stress limit

2.4 Summary

In general, unitized curtain walls of today, even the simpler types, are far more sophisticated products than their early counterparts, though many of the earliest walls are still performing admirably. Fifty years of experience and development have eliminated the major difficulties of the pioneering designs, resulting in better products. (AAMA, 1996) Beginning with the relatively simple, but innovative concept of the early 1950's – a series of window units and panels joined and supported by simple framing members. Curtain wall technology has developed, over the years, into a proliferation of highly engineered designs.

Throughout this development, however, the basic principles of good curtain wall deign have not changed. Recognition of these principles has grown with experience, and the criteria of good design have now become well defined. And, as with any vital and developing product, the industry continues to find ways fo improving performance.

Methods of analysis, similar to some of those mentioned in this chapter, will be utilized in this dissertation to analyze of untized curtain wall system nowadays.

CHAPTER 3

HISTORY OF DEVELOPMENT OF CURTAIN WALL SYSTEM

Prior to the design and analysis of curtain wall system, first of all, let's start from the history of Curtain Wall System.

3.1 History of curtain wall system development

Modernist architects discarded the decorative styles of the 19th century and sought to merge architecture with industry. The result was a simple, logical, functional building style, as much industrial as artistic.

The first curtain wall was designed by German Architect Walter Gropius (1883-1969) who was invited to teach at art school in Germany called the Bauhau ("Building House"). When the Bauhaus moved from Weimar to Dessau in 1926. Gropius constructed the new campus according to his philosophy of clean, functional, modern design. Gropius's most important contribution was the so-called "Curtain Wall", the exterior wall of glass that also displays the building's interior design. Gropius became an influential teacher in America and a founder of what has come to be known as the International Style in architecture.

Fig.7 - Walter Gropius (1883-1969)

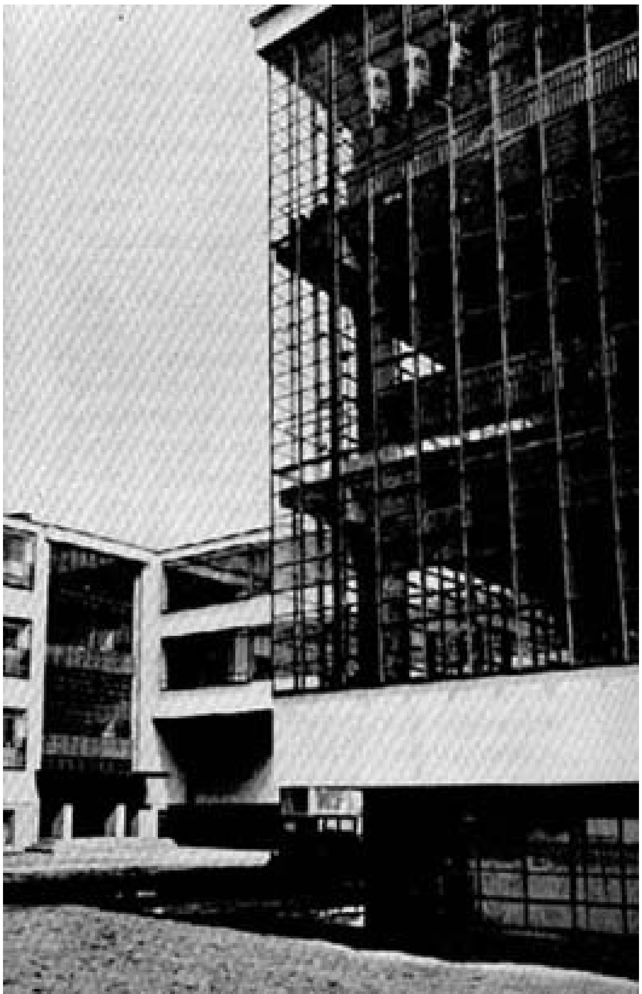


Fig. 8 – The Bauhaus (the early curtain wall system was shown)

Fig. 9 – The Bauhaus

The Curtain walls nowadays, evens the simpler types, are far more sophisticate products than their early counterparts, though many of the earliest walls are still performing admirably. More than fifty years of experience and development have eliminated the major difficulties of the pioneering designs, resulting in better products. Beginning with the relatively simple, but innovative concept of the early 1950's, a series of window units and panels joined and supported by simple framing members. Curtain wall system technology has developed, over the years, into a proliferation of highly engineered designs.

Throughout this development, however, the basic principles of develop good curtain wall system have not changed. Recognition of these principles has grown with experience, and the criteria of good design have now become well defined. And, as with any vital and developing product, the façade industry continues to find ways of improving performance.

3.2 Advantages of unitized curtain wall system compare with stick and semi-unitized curtain wall systems

There are several systems for aluminium curtain wall system, including stick system, semi-unitized system and unitized system. (Information from, AAMA, 1996)

a) Stick wall system.

This is the earlier design of curtain wall technology. The wall is installed piece by piece. Usually, the mullion members (which is vertical member) are installed first, followed in turn by the transom members (which is horizontal rail member), and finally the glazing or window units. However, in designs accenting the horizontal lines the process may be altered to first install the larger transoms. In either case, the transom and mullion members are often long sections designed to either be interrupted or extended through at their intersections.

The stick wall system was used extensively in the early years of metal curtain wall development, and is still widely used in greatly improved versions. Some contractors consider it to be superior to other systems.

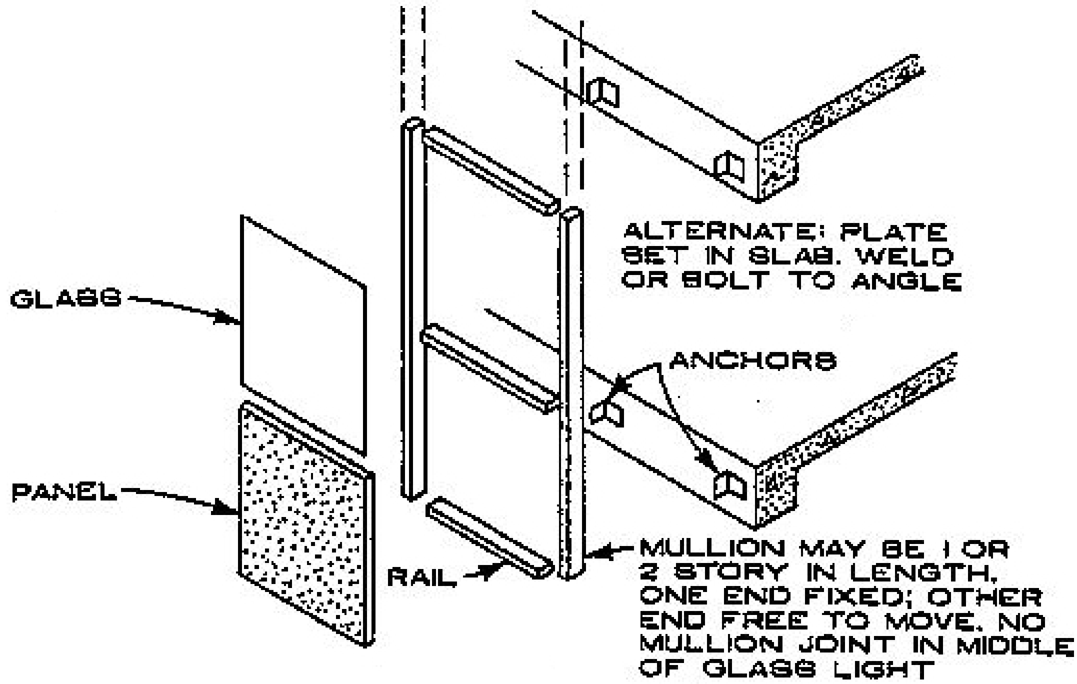


Fig.10 – Diagram to illustrate the stick wall system

The characteristics of this system are its relatively low shipping and handling costs, because of minimal bulk, and the fact that it allows some degree of dimensional adjustment to site conditions.

Its disadvantages are the necessity of assembly in the construction site, rather than under controlled factory conditions, and the fact that pre-glazing is obviously impossible.

b) Semi-unitized System (Hybrid system)

After a period of time, semi-unitized design was occur in curtain wall technology. In this system, the mullion members are separately installed first, then pre-assembled framing units are placed between them. These units may be full story height, or they may be divided into a spandrel unit and a vision glass unit.

Hybrid system is advantage to use when for long span of two floors, which can be reinforced by steel.

This system need large amount of labour for field jointing work and the erection time is comparatively greater.

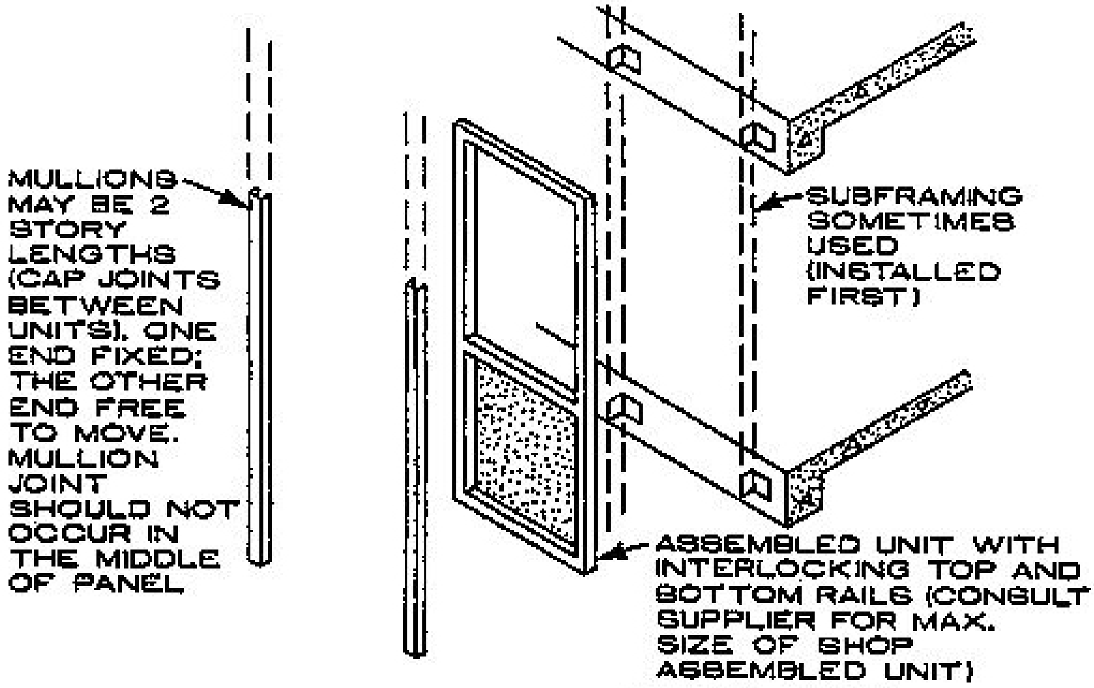


Fig. 11– Diagram to illustrate semi-unitized curtain wall system

c) Unitized curtain wall system

For modern technology, unitized curtain wall system was invented. This system is composed entirely of large frame units pre-assembled at the factory. The mullion member join to the top and bottom transom member, and with a vision glazed glass panel.

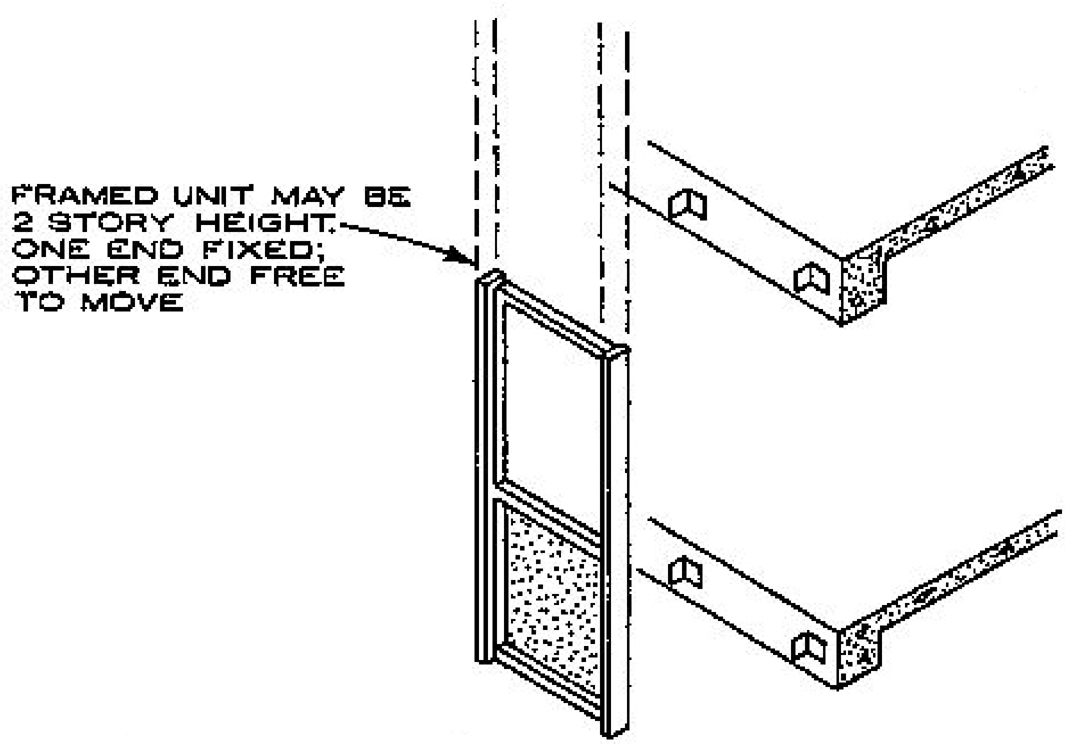


Fig. 12 – Diagram to illustrate unitized curtain wall system

Fig. 13 – An Unitized Curtain Wall Panel.

The production of whole panel are under controlled at the factory, where the process can be carefully inspected, and facilitates rapid enclosure of the building with a minimum of field labor and relatively few joints.

There are 3 curtain wall systems, based on the method of installation, which have been most commonly used to date. It should be obvious that aluminum curtain wall design, contrary to variable condition, is by no means limited to grid patterns, or to patterns accenting either vertical or horizontal lines. More and more, other forms of aesthetic expression are appearing, such as virtually flush walls, walls with little or no exposed framing, walls in which exposed metal serves as a permanent form for concrete framing or fireproofing, and other fresh new concepts.

Perhaps in the future, some of these innovations will become common systems deserving identification, but at present no attempt is being made to tag them. They are referred to simply as ‘other system’, and as the design potentials of aluminium curtain wall are further explored there will certainly be more systems other than the aforesaid typical systems.

3.3 Modern curtain wall system – Unitized curtain wall system

The Unitized curtain wall is the most airtight and weather resistant cladding and exterior wall system available. A glass and aluminum curtain wall fabricated in factory and installed as a panel system is referred to as a unitized curtain wall system. Unitized curtain wall will comprise glass vision panel and spandrel panel mounted in a prefabricated aluminium frame. Most of the system components are assembled in a plant under controlled working conditions. This promotes quality assembly and allows for fabrication lead-time and rapid closure of the building.

The unitized system is assembled on the building as panels. The structural section around the panel is fabricated as half sections instead of a whole section, which mate at assembly time to form the curtain wall system. The panels are installed in shingle fashion, starting either from the bottom or top of the building and going around each floor until the whole building is dressed up.

While the unitized system offers many advantages with respect to quality assembly and speed up the site construction time, there is one design concern with respect to installed performance and durability. In a unitized system, there are three joint along every mullion and transom. These include the two glasses to aluminium joints and a third joint at the junction between the half mullions and half rails. Should an air or water leak develop at the third joint, there is usually no practical method of accessing the in-between panel joint of repair unless the manufacturer has provided a serviceable joint system design.

In a unitized system, the manufacturer must rely on qualified installers to ensure that the air seals are properly installed between the split mullions. Nevertheless, the unitized system is the most popular façade system according to one manufacturer and it has performed satisfactorily when installed correctly.

3.4 Design of curtain wall system

The Façade Engineers and Designers are involved in the design criteria, the design and installation of the curtain wall of the building.

Curtain wall system is a cladding system, made of contiguous elements, which envelopes the building structure on which it huge like a curtain and excludes wind and weather, includes the air conditioned environment, but resists no building load. It generally has an aluminium frame structure and glass vision panels and spandrels which can be of any panel material, for examples, glass, metal, stone, compressed cement or sandwich panel.

To perform satisfactorily curtain wall system, as an exterior wall system must meet several performance requirements. These including,

- Structural integrity
- Provision movement
- Weather tightness
- Moisture control
- Thermal insulation
- Sound transmission

Each of above design concept will be detail illustrated in Chapter 4.

3.5 Analysis of curtain wall system

Obviously all exterior walls, of whatever materials, are subject to, and must withstand the ravaging effects of nature. These nature forces are sunlight, temperature, water, wind and gravity. Except for gravity, the intensity and relative significance of these forces vary somewhat from one region to another, but all of them must be considered, and their effects provided for, in all locations. They may act upon the wall either individually or more often in concert, but to understand their impact on design requirements the effects of each should be separately examined.

An analysis of the effects of these natural forces reveals the major problem area to be anticipated. Experience verifies that in the design of unitized curtain wall, there are generally three matters of chief concern;

- Structural integrity
- Provision for movement
- Weathertightness

Of course, there are a number of other considerations, most of which are of less critical importance and some of which vary in importance with the location and type of building. The following are the steps for analysis,

- Loading assumption
- Finite element analysis
- Structural member analysis

The above steps will be detail shown in the Chapter 5.

CHAPTER 4

DESIGN OF CURTAIN WALL SYSTEM

4.1 Introduction

Curtain walls are the most abused of building elements being subjected to wind loading, extreme events, building movements, sudden temperature changes, driven rain, atmospheric pollution and corrosion (Hunton et al. 1987).

This chapter discusses the characteristic of major components material for Unitized Curtain Wall System and the need for a better technical awareness in Curtain Wall design through a much greater involvement for technical concerns.

Curtain wall system always gives people a sense of simplicity and regularity. Some people even simply think that this system is just an assembly of glass, aluminium, steel, screw and sealant. Curtain wall system, apart from its appearance, functions as an external enclosure to protect the building from weather and to achieve pressure-equalization between the outdoor and indoor environment; its construction is not only an assembly of several components, but an advanced technology which involves sophisticated calculation.

4.2 Natural forces and their effects on curtain wall system

Obviously all exterior walls, of whatever material, are subject to, and must withstand the ravaging effects of nature. Prior the discussion of design of curtain wall system, the following are the effect created by natural environment .

4.2.1 Sunlight

Sunlight, which human could not live without it. It provides warmth, color, visual definition and life itself. But it also creates certain problems in curtain wall design. One of these problems is its deteriorating effect on organic materials such as color pigments, plastics and sealants. The actinic rays, particularly those found in the ultra-violet range of the spectrum, produce chemical changes which cause fading or more serious degradation of materials It is essential, therefore, that materials and finishes vulnerable to such action be thoroughly investigated before being used, and that sealants be tested for resistance to ozone attack and ultra-violet radiation. (AAMA 1996)

Another problem resulting when uncontrolled sunlight passes through the wall is the discomfort of glare and brightness and degradation of interior furnishings.

Conventionally, such effects are combated by use of some type of shading device, either inside or outside of the vision glass. A newer approach, gaining in favor, is the use of glare-reducing or reflective types of glass which provide relief without restricting vision.

4.2.2 Temperature

Temperature creates two kinds of problems in curtain wall design, they are:

- the expansion and contraction of materials; and
- the necessity to control the passage of heat through the wall.

It is the effect of solar heat on the wall which creates one of the major concerns in aluminium curtain wall design, which is thermal movement. Temperature fluctuations, both diurnally and seasonally, that critically affect wall details. All building materials expand and contract to some extent with temperature changes, but the amount of movement is greater in aluminium than that in most other building materials.

The control of heat passage through the wall affects both heat loss in cold weather and heat gain in hot weather, the relative importance of the two varying with geographic location. Thermal insulation of opaque wall areas become and important consideration when such areas constitute a substantial part of the total wall area, but when vision glass areas predominate, the use of insulating glass, and the minimizing of through metal or 'cold bridges' are more effective in lowering the overall U-value of wall.

4.2.3 Water

Water, in form of rain, snow, vapor or condensate, is probably the most persistent cause of potential trouble. As wind-driven rain, it can enter very small openings and may move within the wall and appear on the indoor face far from its point of entrance. In the form of vapor it can penetrate microscopic pores, will condense upon cooling and, if trapped within wall, can cause serious damage that may long remain undetected. (Quirouette 1999)

Leakage may be a problem in a wall built of any material. Most masonry walls, being porous, absorb a good deal of water over their entire wetted surface, and under certain conditions. Some of this water may penetrate the wall, appearing as leaks on the indoor side. But the materials used in metal curtain wall are impervious to water, and potential leakage is limited to joints and openings. Though this greatly limits the area of vulnerability, it greatly increases the importance of properly designing the joints and seals.

4.2.4 Wind

Wind acting upon the wall produces the forces which largely dictate its structural design. On the taller structures in particular, the structural properties of framing members and panels, as well as the thickness of glass, are determined by maximum wind loads.

Winds also contribute to the movement of the wall, affecting joint seals and wall anchorage. The pressures and vacuums alternately created by high winds not only subject framing members and glass to stress reversal, but cause rain to defy gravity, flowing in all directions over the wall face. Thus wind must be recognized also as a major factor contributing to potential water leakage.

4.2.5 Gravity

Gravity, unlike the other natural forces, is static and constant, rather than dynamic and variable. Because of the relatively light weight of materials used in curtain walls, it is a force of secondary significance, rarely imposing any serous design problems. It causes deflections in horizontal load-carrying members, especially under the weight of large sheets of heavy glass, but because the weight of the wall is transferred at frequent intervals to the building frame, gravity forces affecting structural design are generally small in comparison with those imposed by wind action. But far greater gravity forces, in the form of floor and roof loads, are acting on the building frame to which the wall is attached. As these loads may cause deflections and displacements in the frame, the connections of the wall to this frame must be designed to provide for sufficient relative movement to insure that displacements do not impose vertical loads on the wall itself.

4.3 Design Consideration

Curtain wall system is a cladding system, made of contiguous elements, which envelopes the building structure on which it huge like a curtain and excludes wind and weather, includes the air conditioned environment, but resists no building load. It generally has an aluminium frame structure and glass vision panels and spandrels which can be of any panel material, for examples, glass, metal, stone, compressed cement or sandwich panel. To perform satisfactorily, before the structural analysis, curtain wall system must meet several performance requirements.

An analysis of the effects of these natural forces reveals the major problem areas to be anticipated. Experience verifies that in the design of unitized curtain wall system, there are generally three major matters of chief concern. They are,

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

Of course there are a number of other considerations, most of which are of less critical importance and some of which vary in importance with the location and type of building. Let start to review briefly these major considerations applying in all cases.

4.3.1 Structural integrity

Because structural failure may jeopardize human life, the structural integrity of the wall may be said to be the primary concern in its design. But the structural design of curtain wall involves the same procedures as used in any other wall, and deficiencies in this respect are less likely to occur than deficiencies in providing for movement and weather tightness requirements, which by comparison present unique problems in metal construction. Structurally, the requirements of stiffness rather than strength usually govern, and though excessive deformations may, in some cases, lead to damage, such rare instances of actual failure as have occurred have, for the most part, been limited to faulty anchorage details.

As vertical loads in the wall system are relatively light structural design is chiefly a matter of providing proper resistance to lateral wind forces. This is a routine procedure provided that the nature and magnitude of the wind loads are known. But herein may cause the problem. There are a fairly good knowledge of wind loads on low and medium height buildings but still have much to learn about the nature and intensity of such loads on tall structures.

It is well known that maximum wind velocities, and consequently design wind loads, vary not only with geographic location but also with height above the ground. It is less generally recognized that the nature of the building's surroundings, suburban character or dense urban building, are even more important influences on wind action. Another fact not generally recognized, even in some of the major building codes, is that the wind loads, acting on the skin of the building are of a different character and magnitude than those which govern the design of the building frame. As compared with the overall design loads, those acting on the wall are more severe in intensity, have a specific rather than cumulative effect, and change more drastically and more rapidly. (AAMA 1996)

Often too little significance is attached to the negative wind loading, or suction forces, acting on the wall, and the fact that internal building pressures due to air conditioning may augment such forces. Many designers tend to think only in terms of wind pressure, whereas in fact, even with moderate winds, more of the total perimeter wall surface of a rectangular building is likely to be subjected toa vacuum than to pressure.

On high-rise buildings, these negative pressures are usually maximum near the building corners, where they may be more than twice as great as any positive load on the wall. When wind damage does occur, it is more often in the form of a blow-out than a blow-in. This explains why the most common deficiency in structural design is the failure to provide adequate resistance, particularly in anchorage details, to the suction action of the wind.

4.3.2 Provision for movement

A most important consideration in designing any aluminium curtain wall is necessary to ample provision for movement. No building is a static thing, and this goes double for metal curtain wall. Movement is constantly taking place, such as movement within the wall components themselves, relative movement between the components, and relative movement between the wall and building frame to which it is attached. These movements are caused not only by temperature changes, but by wind action, by gravity forces and by deformations or displacements in the building frame. To disregard such movements in designing the wall is an urgent invitation to trouble.

The effect of temperature changes is of course uniquely significant, because of the relatively high coefficient of expansion of aluminum, but the amount of such movement is predictable. In most parts of the country, the probable seasonal range of metal surface temperature is at least 150F, and in some parts it may be as much as 200F. This translates into a movement of from 1/4” to 5/16” in a 10-foot length of aluminum. In a sheet of glass used alongside the aluminum the amount of movement will be less than half as much. (Quirouette 1999)

Movement due to the other causes mentioned are generally not accurately predictable, but may be equally significant. Whatever the cause, however, the problem of providing for movement reduces to the problem of joint design, because it is at the joints that movement must be accommodated. It becomes axiomatic, therefore, that the secret of a functionally successful curtain wall lies in the design of its joints.

Consequently, the detailing of the joints is the most critical, and often the most difficult aspect of any curtain wall design. It dose not necessarily follow, however, that by using larger wall units and thus fewer joints the problem will be simplified. This is seldom the case. The larger the units, or the longer the members, the greater will be the amount of movement to be accommodated at each joint, and this tends to complicate, rather than simplify the joint design.

Provision must be made, of course, for both vertical and horizontal movement in the plane of the wall, either by some kind of slip joints or bellows action. It should be recognized, though, that expansion and contraction are not necessarily translated entirely into displacement. In some situations they can be absorbed, to some degree at least, by increased stress within the member, resulting in a calculated deformation, and often they are accommodated by a combination of stress and deformation. Except in a few cases, however, reliance upon stress increase alone to accommodate expansion is not advisable, as excessive bending or buckling may result.

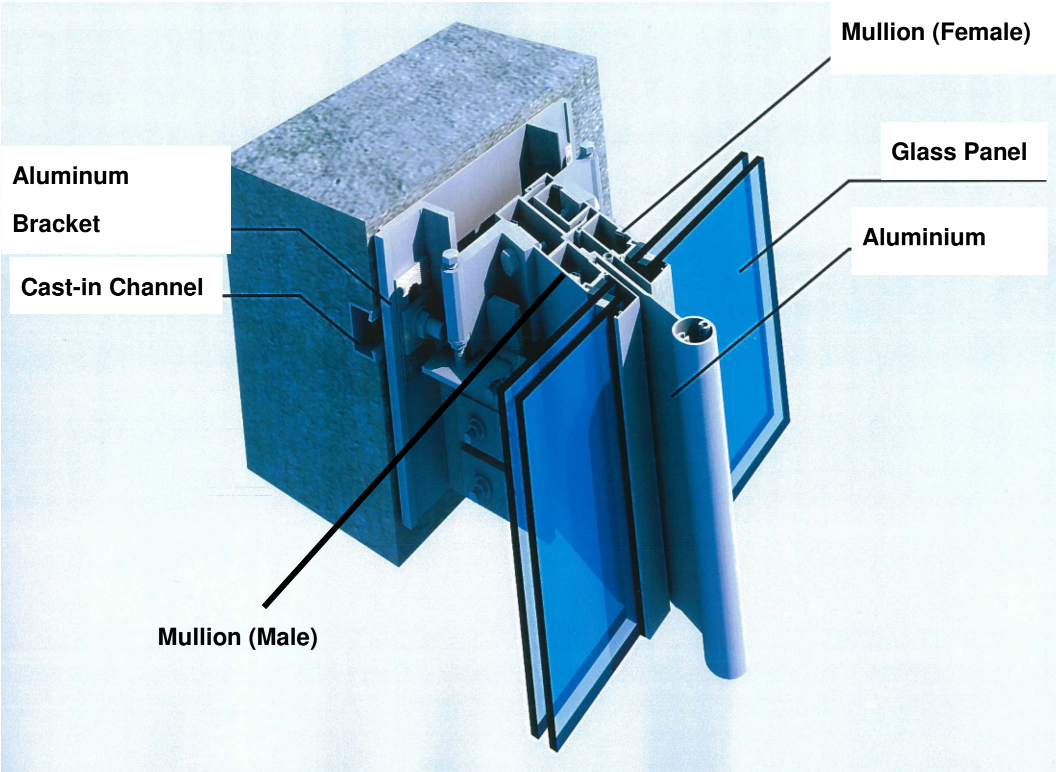


Fig.14 – Fixing details of unitized curtain wall system

Figure 14 shown the fixing detail of unitized curtain wall system with slot hole design at the connection, these design involved the movement concern and concrete tolerance of the system. In this figure, male mullion indicates the vertical member of left side unitized curtain wall panel while female mullion is from right side curtain wall panel.

4.3.3 Weather tightness

Weather tightness means protection against both water leakage and excessive air infiltration. It depends in large measure on adequate provision for movement, and is closely related to proper joint design. Undoubtedly, a major share of difficulties experienced with metal curtain wall over the years has been due to the lack of weather tightness. Water leakage was an all-too-common occurrence in the earlier walls, due to faulty design, materials or workmanship, or a combination of these. But with improved materials and design techniques its prevention has now become the rule rather than the exception. By comparison, excessive air leakage is les critical and more easily prevented.

Large wind load causes rain water to flow in all directions over the windward surface of a panel, and on surfaces of impervious materials much of it tends to collect at the joints, the major points of vulnerability. Early in the history of metal curtain wall experience it became apparent that to provide all joints at their outer surface with a permanently waterproof seal was essentially impossible, because of their continual movement, and this approach to weather tightness was soon abandoned. Instead, two other methods have been developed for preventing leakage through the wall, and either of these, when intelligently applied, is highly dependable. One is referred to as the 'internal drainage' or 'secondary defense' system, and has long been used by competent designers, example shown in Figure 16. The other is the 'pressure equalization' method, a more recent development in metal curtain wall technology, refer to figure 17.

The internal drainage method is based on the philosophy that it is impractical if not virtually impossible to totally eliminate, for any length of time, all leakage at all points in the outer skin of the wall, but that such minor leakage can be prevented from penetrating to the indoor face of the wall or even remaining within the wall. This is accomplished by providing within the wall itself a system of flashing and collection devices, with ample drainage outlets to the outdoor face of the wall.

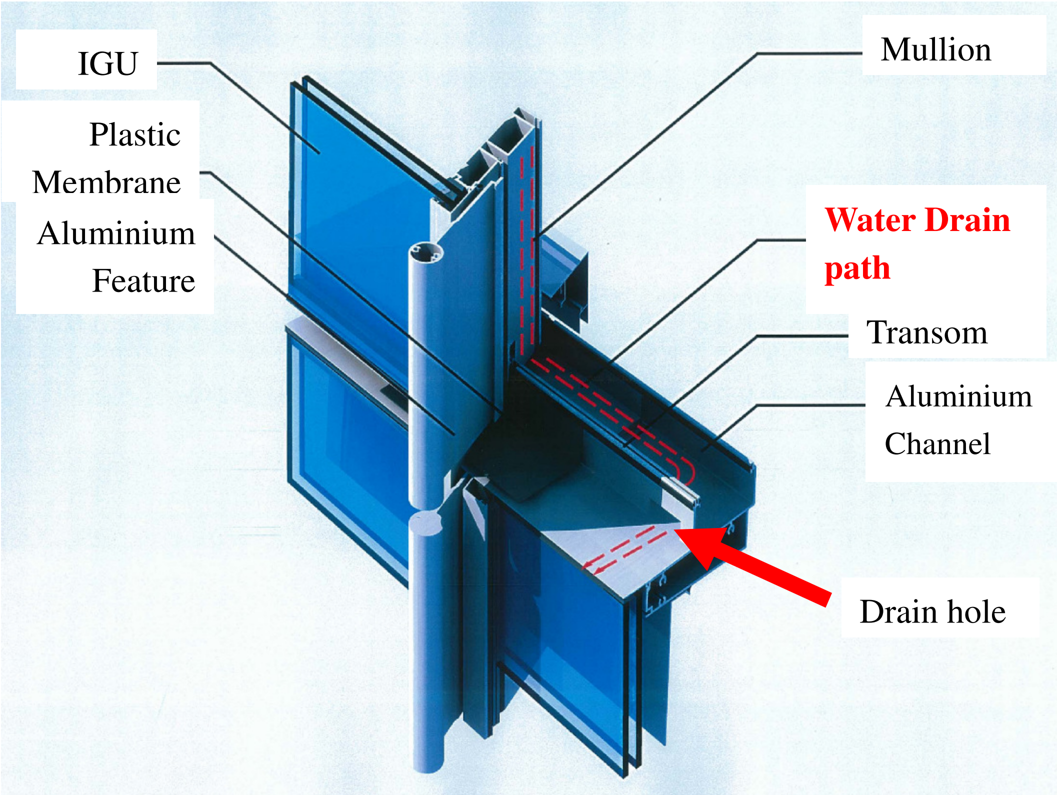


Fig. 15 – Drainage path in unitized curtain wall system

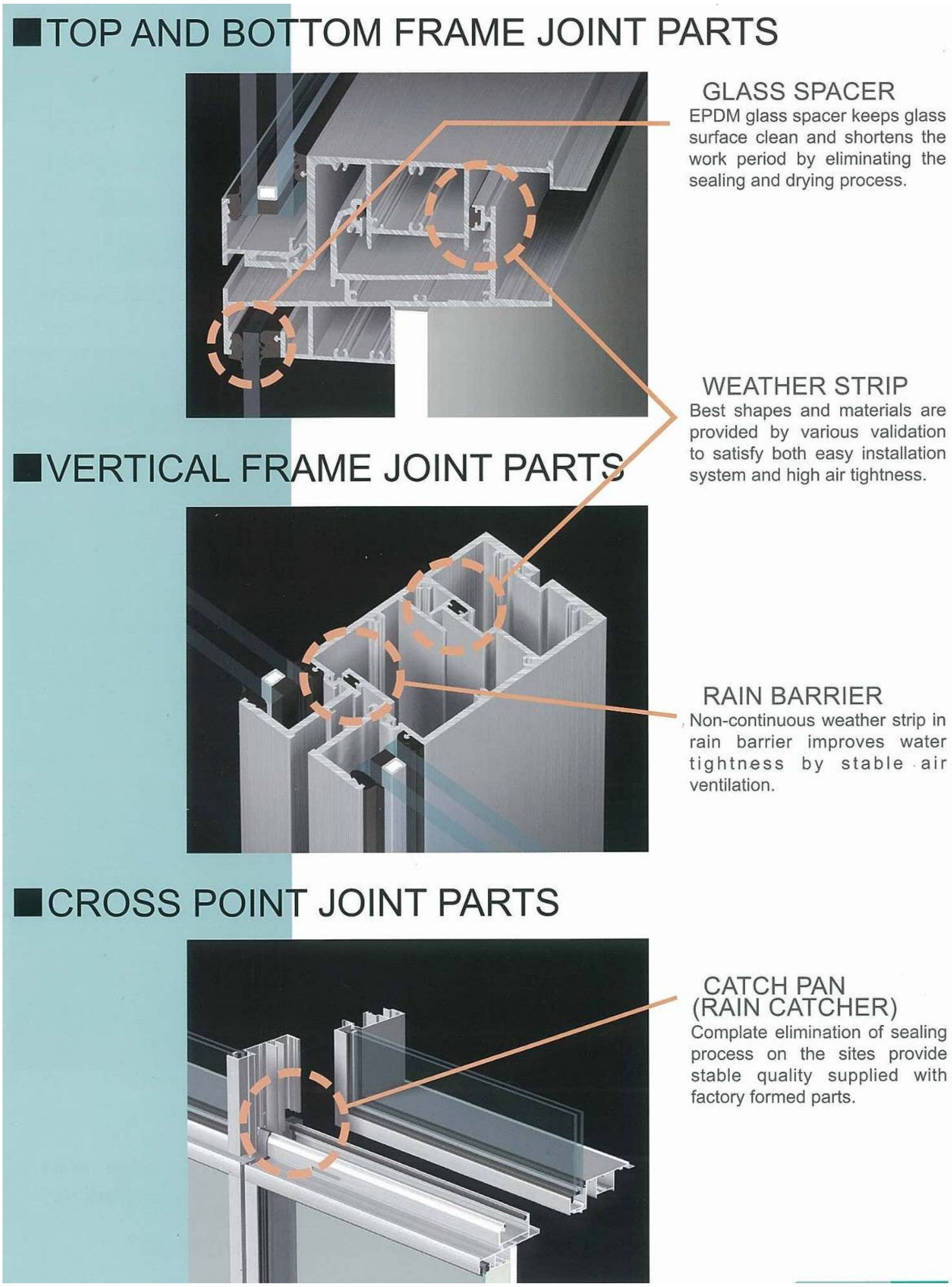


Fig.16 – Design concern of weather tightness in unitized curtain wall system

The method of pressure equalization, based on the 'rain screen principle', is generally a more sophisticated and complex solution, but is claimed by its proponents to be completely infallible when properly applied. It required the provision of a ventilated outer wall surface, backed by drained air spaces in which pressures are maintained equal to those outside the wall, with the indoor face of he wall being sealed against the passage of air. An example is shown in figure 15.

The successful use of these methods depends on a clear understanding of the action of wind driven rain, careful detailing and, of course, proper installation. And in both cases ample weep holes or drainage slots, strategically located and properly baffled, play a critical role.

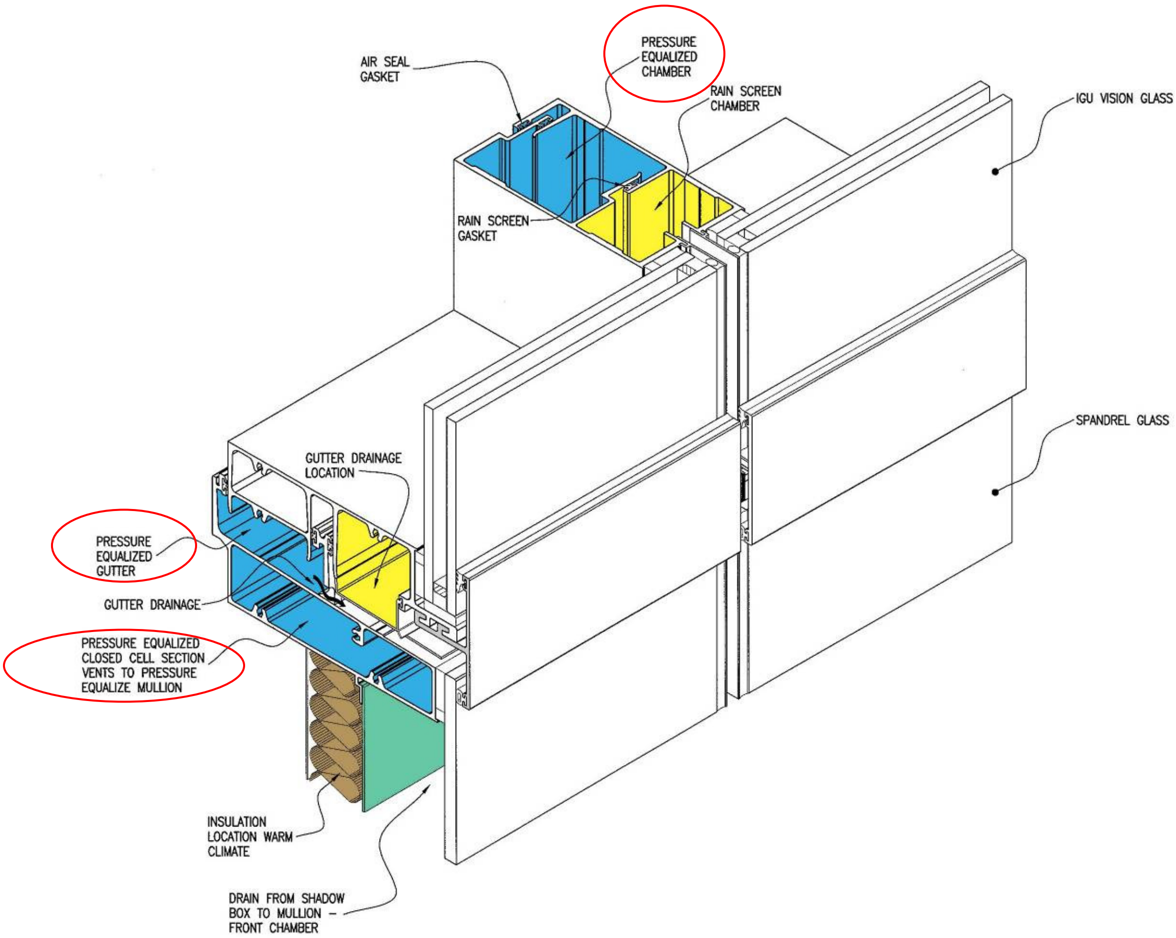


Fig.17– Design concern of pressure equalized in unitized curtain wall system

4.3.4 Moisture control

Because metal and glass are not only impermeable to moisture, and thus highly efficient vapor barriers, but also have low heat retention capacity, the control of condensation is essential in any metal curtain wall design. Unless proper controls are provided, moisture, or even frost, may occur on the indoor face of the wall, and condensation may collect within the wall, causing damage which can become serious before it is detected. Fortunately, the control of moisture is a comparatively simple matter, provided that the problem is anticipated and preventive measures are incorporated in the wall when it is built.

An understanding of the causes of condensation, where it will likely occur, and how to minimize its potential damage is essential, if trouble is to be avoided. But to explain these matters is beyond the scope of this summary review, intended only to flag out the importance of the matter. In capsule form, the important precaution to be remembered are as follow:

- A vapor barrier should be provided on or near the indoor side of the wall;
- Impervious internal surfaces should be sufficiently insulated to keep them warmer than the dew point of the air contacting them;
- Provision should be made for the escape of vapor to be outdoors; and
- The wall should be so detailed that any condensation occurring within it will be collected and drained away.

4.3.5 Thermal insulation

In some cases the insulating value of the wall may be one of the major design considerations, an example refer to figure 18. Whether to reduce heat loss and prevent condensation in cold weather or to minimize heat gain and air conditioning cost in hot weather, reduction of the overall U-value of the wall is usually a good long-term investment. Metal and glass are materials which inherently have low resistance to heat flow, but with proper attention to details aluminum curtain walls can be designed to provide good thermal performance. Generally this is accomplished by minimizing the proportion of metal framing members exposed to the outdoors, eliminating thermal short circuits by means of ‘thermal breaks’, using double rather than single glazing, and providing good insulation I the large opaque areas of the wall.

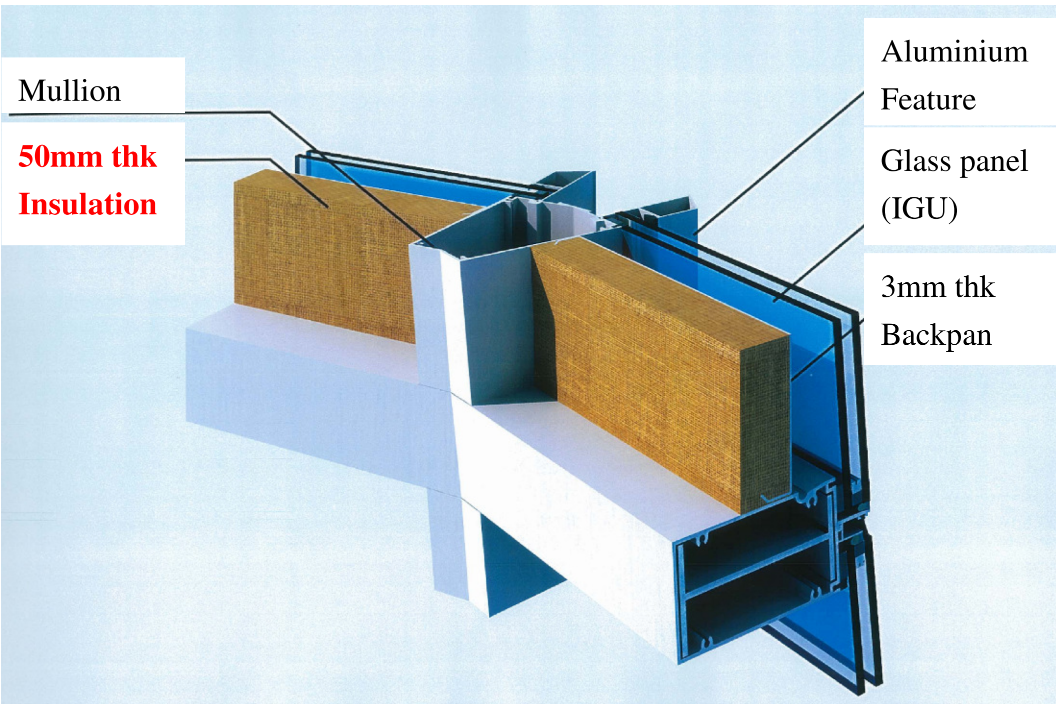


Fig. 18– Insulation installed in unitized curtain wall system

4.3.6 Sound transmission

Under normal conditions, even in densely built urban areas, metal curtain walls compare favorably with any other wall construction having equivalent fenestration, as a barrier to airborne sound. However, the increasing concern with noise pollution and the mushrooming of building near airports has focused attention on the need for ‘soundproofing’ exterior walls. According to the law of mass, the transmission of sound through any barrier is inversely proportional to the mass of the barrier, and any lightweight construction such as metal curtain wall can claim no natural advantage as a sound barrier. But with careful detailing, based on an understanding of the principles of sound transmission, aluminum curtain walls have been designed to provide quiet enclosures near many airports.

It must be remembered that the efficiency of a barrier to airborne sound depends, in large degree, upon its weakest link, and the weak links in most walls are glazed areas and openings, however small the latter may be. Where a high degree of sound insulation is required, air leakage through the wall must be minimized, and double glazing, well separated and sealed, is usually essential.

4.4 Glass and glazing

Unitized curtain walls often provide the appearance of being all glass. Some are glass with metal spandrel covers and some curtain walls incorporate granite facing panels in the spandrel frames. The glass of vision areas and the glass of spandrels and stone facings are specialty products.

Glass for curtain walls is available as float, tinted (heat absorbing), wired glass, patterned and cathedral glass. Float glass may be heat treated to become heat strengthened glass or tempered glass to provide greater resistance to thermal and mechanical stresses. For greater safety, laminated glass is also available. Vision glass is usually fabricated from float glass. However, if additional strength or safety is required, then heat strengthened, tempered, laminated or wire glass may be used. Vision glass may be heat absorbing (tinted) or heat reflective (coated). Laminated glass or wire mesh glass are used for impact strength and fire resistance.

Vision glass for a curtain wall may be single, double or triple glazed. In general, vision glass is clear. It is available in various thicknesses, it is between 6mm to 25mm thick. It is usually assembled into an IGU to provide heat loss (or heat gain) control and better condensation resistance. To describe glass products, the industry has adopted a standard method of surface identification for single, double and laminated glazing units.

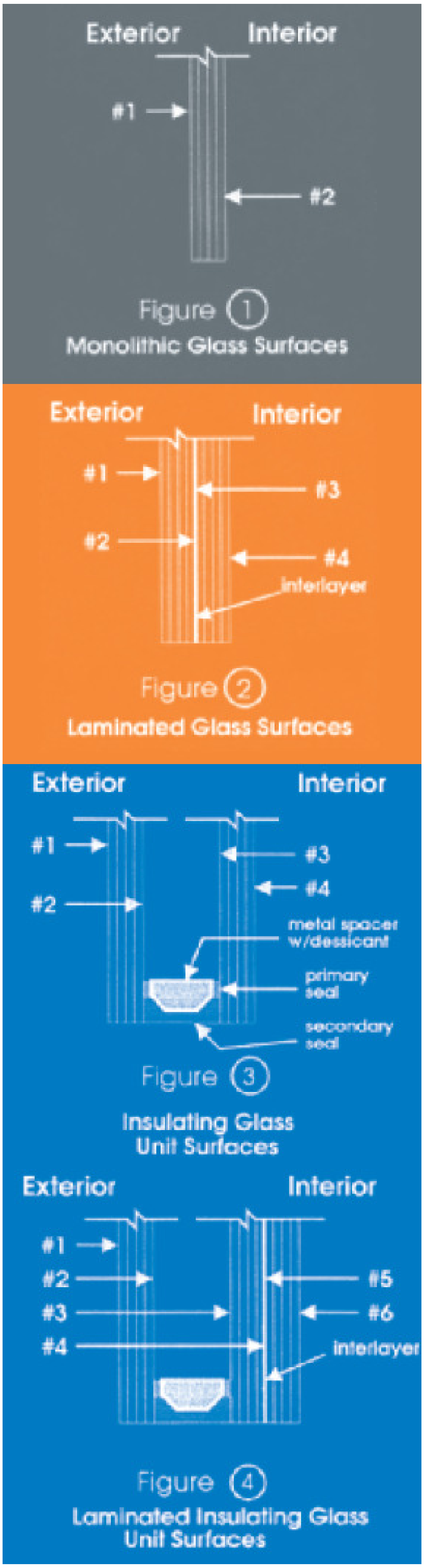


Fig. 19– Cross section diagram to show different types of glass (Quirouette 1999)

A typical IGU consists of two layers of glass with a spacer between the panes. The spacer separates the glass panes to a uniform cavity thickness. The spacer bars may be metal (aluminum) or non-metallic (fiberglass). Fiberglass spacers are used to reduce heat loss at the edge of the IGU or to increase the inside edge glass temperature. They are usually filled with a powder that absorbs humidity (molecular sieve or desiccant) to absorb the residual moisture in the cavity air between the two layers of glass following its fabrication. In general the poweder is placed in all four bars and it lowers the dewpoint temperature of the IGU cavity air to -60 degree C or less.

The glass panes are held together with either a single seal of polysulfide, polyurethane or hot-melt butyl or with a dual seal consisting of a primary seal of polyisobutylene (PIB) and a secondary seal of silicone, polysulfide or polyurethane. The primary seal is the vapour barrier seal and the secondary seal holds the glass panes together. The secondary seal may be applied to a depth (glass bite) of 6mm to 10mm.

Spandrel glass is often a single layer of heat-strengthened glass with a metallic coating and a polyester opacifying film. The film and coating provide spandrel glass color and safety in case of breakage. Glass thickness and coatings of monolithic spandrel glass vary with the application. A spandrel area may also be enclosed with an IGU to provide uniform color matching of the vision and spandrel.

Architect or designer usually specify IGUs for the vision area. The units may be as simple as double glazed clear float glass with a metal spacer and double seal at the edge or one surface of the IGU may be coated with a low E material, it may be gas filled with argon and equipped with a super spacer for increased R value. The type of units, its purpose and performance requirements should be discussed with the glass supplier.

The installation of an IGU usually requires a clear space of 12mm around the perimeter of the glass. The edges must not come in contact with any metal parts and fasteners must not penetrate into the glazing cavity. IGUs are installed on EPDM, silicone, or neoprene setting blocks, minimum 100mm long by 20mm to 25mm wide (depend on thickness of IGU) by 6mm thick. If silicone is used as the secondary seal of an IGU, neoprene setting blocks must not be specified for this application.

Glass usually does not break without a reason. Projectiles, contact with metal at the edge, excessive torquing of pressure plates, high wind load, earthquake load and differential heating are some reasons for breakage. When the outer pane or the inner pane of an IGU breaks, it is sometimes referred to as thermal breakage. Glass breakage of this type occurs when the temperature of the center of the glass rises above the temperature of the edges (sometimes caused by deep shading) by 30 degree C or more. This can also occur when the sun rises to face a window following a cold night. As the center of the glass warms up faster than the edge, breakage may occur when the temperature difference between the center of the glass and the edge exceed 30 degree C. Similarly, when the outdoor temperature is cold and the indoor surface of an IGU is heated by convection air the glass-to-edge temperature difference may exceed 30 degree C. Heat strengthened and tempered glass do not break when subjected to a temperature difference of 30 degree C.

While glass breakage may occur occasionally, the most frequent cause of failure of an IGU is moisture. When the bottom edge of an IGU is immersed in water for an extended period of time, the water attacks the seals and finally allows glazing cavity air to leak in to the IGU cavity space, eventually fogging or streaking the surfaces between the glass panes. When this occurs there is no recourse except to replace the IGU. The most frequent causes of excessive wetness are the absence of a drained and vented cavity and/or excessive amounts of sealant in the glazing cavities which block drainage paths to the outside.

4.5 Conclusion

The unitized curtain wall system is a marvel of engineering and architecture. A totally non combustible system of glass and aluminium requiring minimal maintenance and providing years of aesthetic quality and building envelope performance. It is most advanced exterior window wall system available for buildings. Most curtain wall suppliers and glazing companies provide the necessary expertise and production capabilities to construct a quality building. However, no architect/designer should design or prescribe a curtain wall system without a general understanding of the characteristics of glass and aluminium curtain wall technology, in particular the assembly requirements, scheduling and testing of the curtain wall in situ or in a laboratory.

CHAPTER 5

ANALYSIS OF UNITIZED CURTAIN WALL SYSTEM

5.1 Introduction

This chapter will demonstrate the analysis of unitized curtain wall system in virtual construction project with my case study. Finite element and structural analysis will be used for analysis the system. The finite element analysis method - Strand 7 was used to study the behavior of glass panel in virtual condition. And, structural analysis method – Space Gass was used to study the behavior of mullion and transom of unitized curtain wall system in virtual condition as well.

5.2 Case study

Project location: MTR Kowloon Station, Hong Kong, China

Tower Name: Cullinan

Fig.20 - Project Photo of “Cullinan”

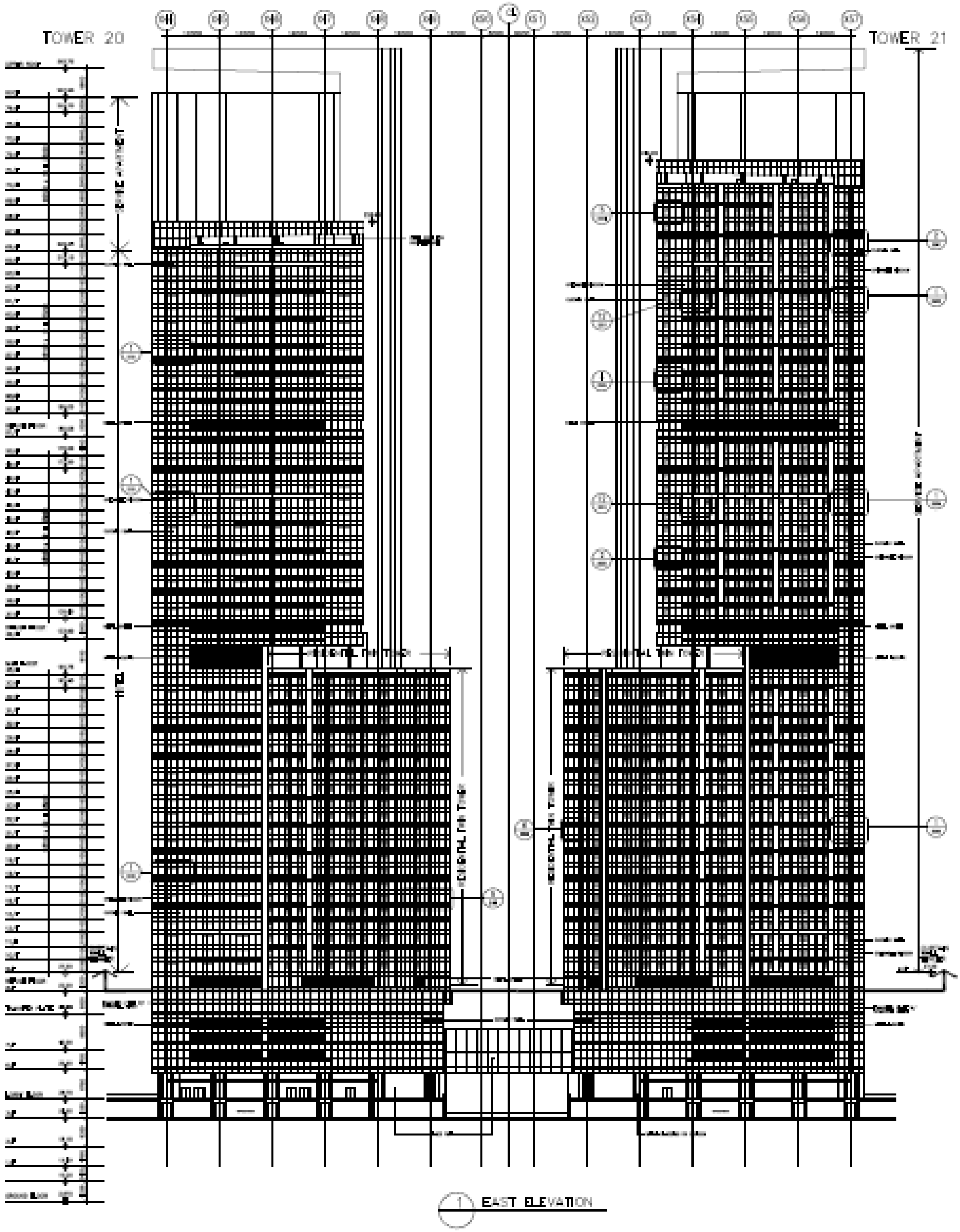


Fig.21 - Elevation plan of “Cullinan”

5.2.1 Wind Pressure Calculation:

The maximum height of this project is about 243 meter. According to "Code of Practice on Wind Effects in Hong Kong 2004" (refer to Appendix A), the wind pressure are derived as follow.

Maximum height of building = 243m

Basic wind pressure = 3.3kPa

For edge zone of the building,

Pressure coefficients, Cp = -1.4 (suction) and +1.0 (pressure)

So,

Design wind pressure = -1.4 x 3.3 = -4.62kPa (suction)

And = +1.0 x 3.3 = +3.3kPa (pressure)

5.2.2 Glass design

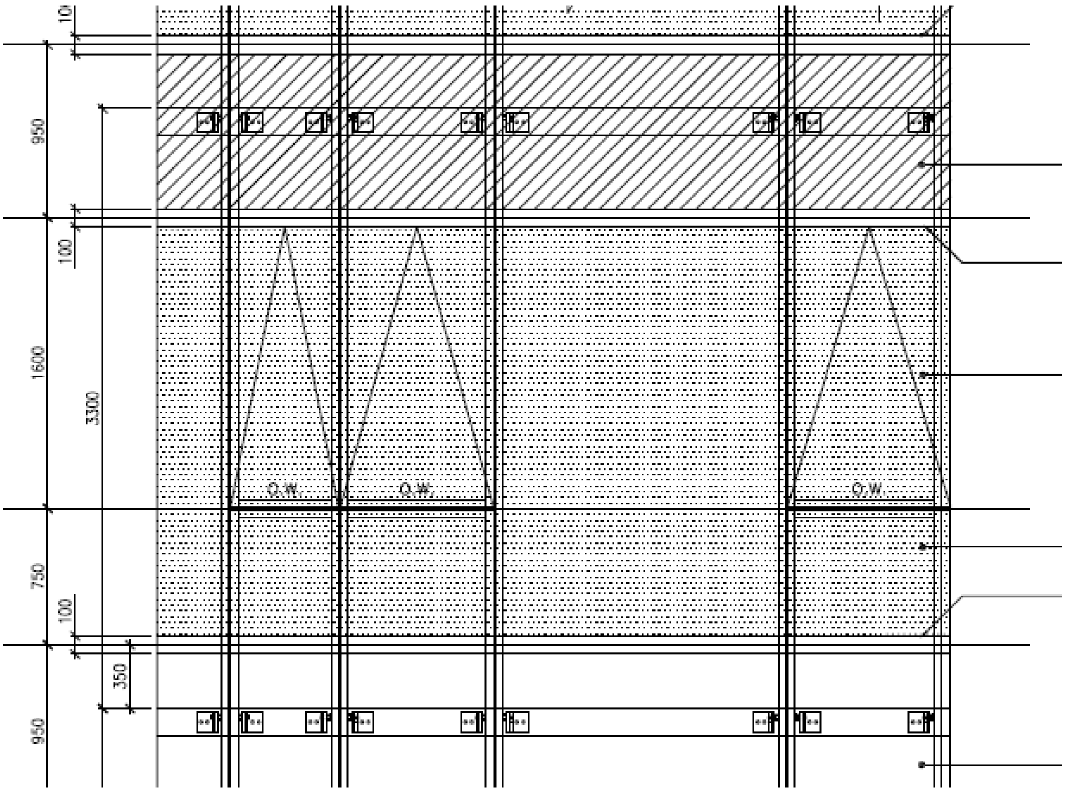


Fig. 22 – Part of elevation of glass panel

1) Vision Glass Design Criteria:

- Figure 22 is extracted elevation plan, the largest size of vision glass panel is 1700mm x 2350mm.

- According to the selection of the Architect, IGU with Fully Tempered Glass will be used.

  IGU consist of two layers of glass with a spacer between the panes, air was filled in between two layers of glass. Thickness of the spacer is 12mm. To design of glass panel, Strand 7 will be used for finite element analysis.

- According to the requirements of Hong Kong Building Department, assume wind load will be share by 2 layers of glass, then each glass is carried 50% of wind pressure.

- 4-side support of the glass panel by mullions and transoms.
- Glass analysis by linear static of Strand 7.

A) Loading Diagram:

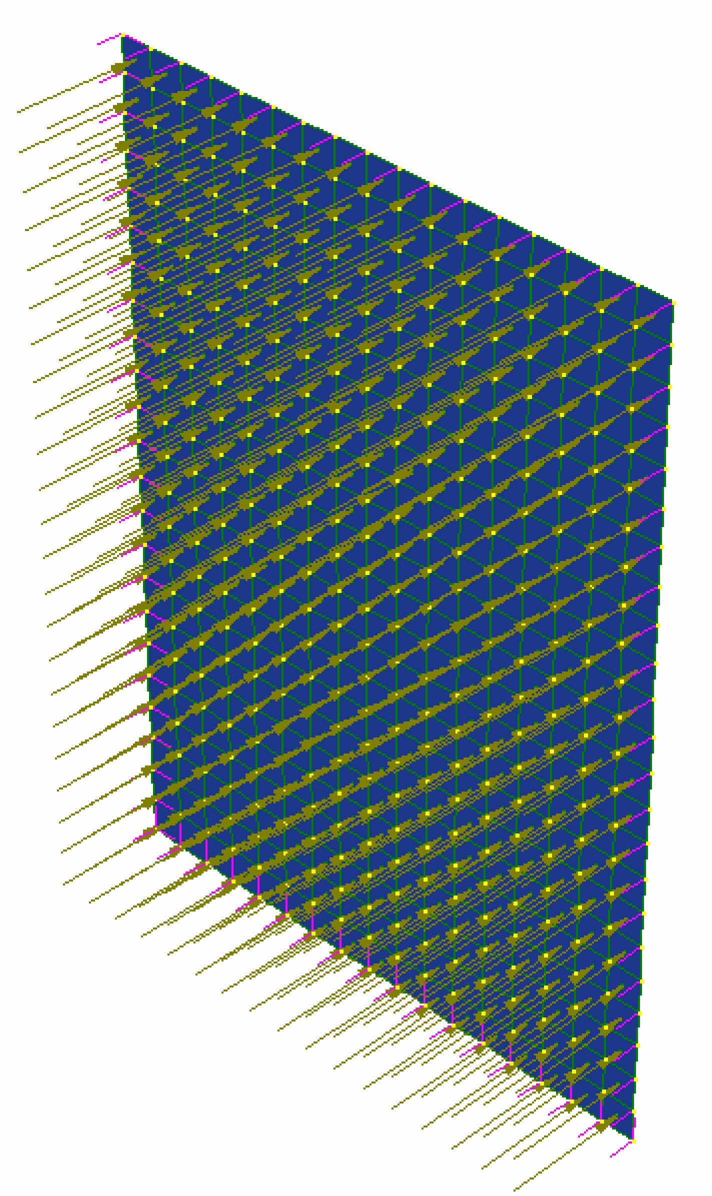


Fig. 23– Load Diagram of vision glass (Strand 7)

Loading data summary:

- Loading pressure = 4.62 / 2 = 2.31kPa
- Glass thickness = 10mm
- Glass size = 1700mm x 2350mm
- Glass with 4 sides supported by mullions and transoms

B) Deflection Diagram:

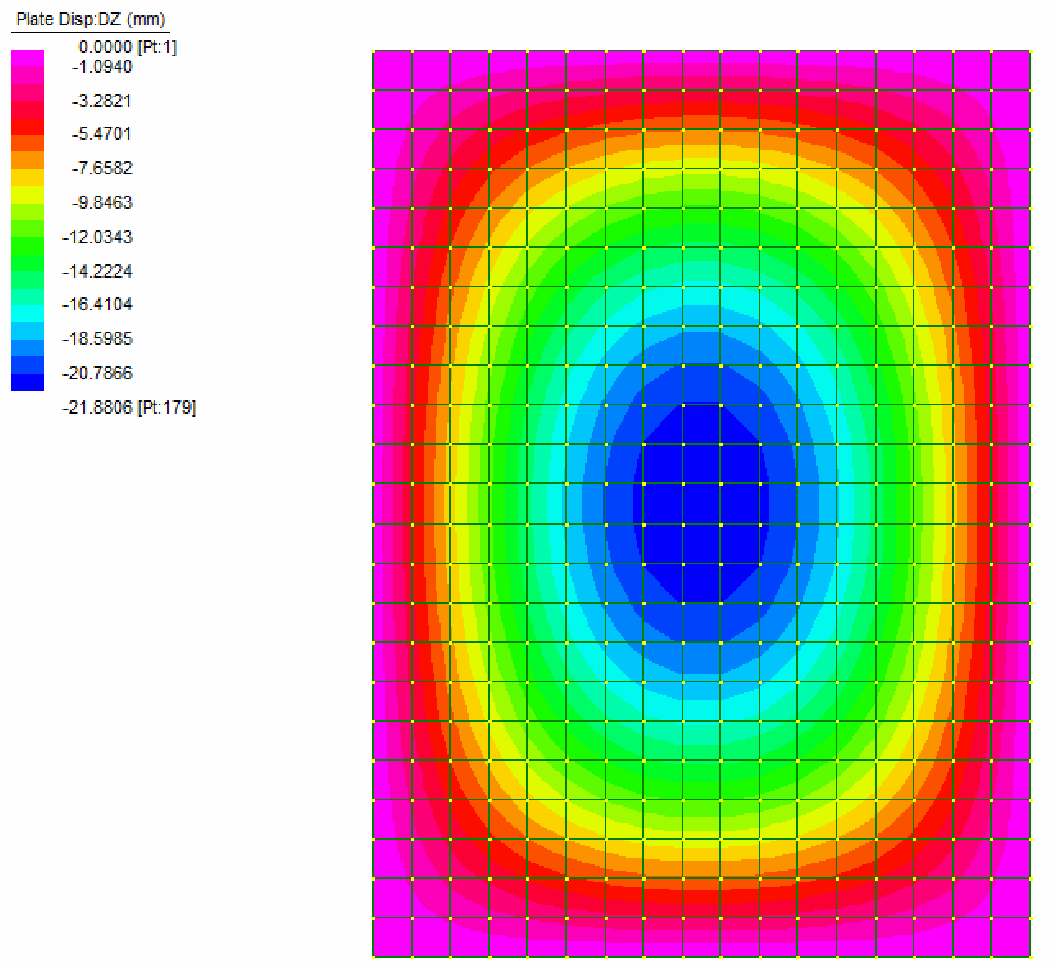


Fig. 24– Deflection Diagram of vision glass (Strand 7)

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

From the result shown in the figure 24, Maximum deflection = 22 mm, which is small than either 28mm and 25mm. So, the result is accepted.

From the contour deflection diagram, the maximum deflection is located at the centroid of the glass. Since the glass was supported by 4 sides, the result is acceptable with the maximum defection at centroid.

C) Stress Diagram:

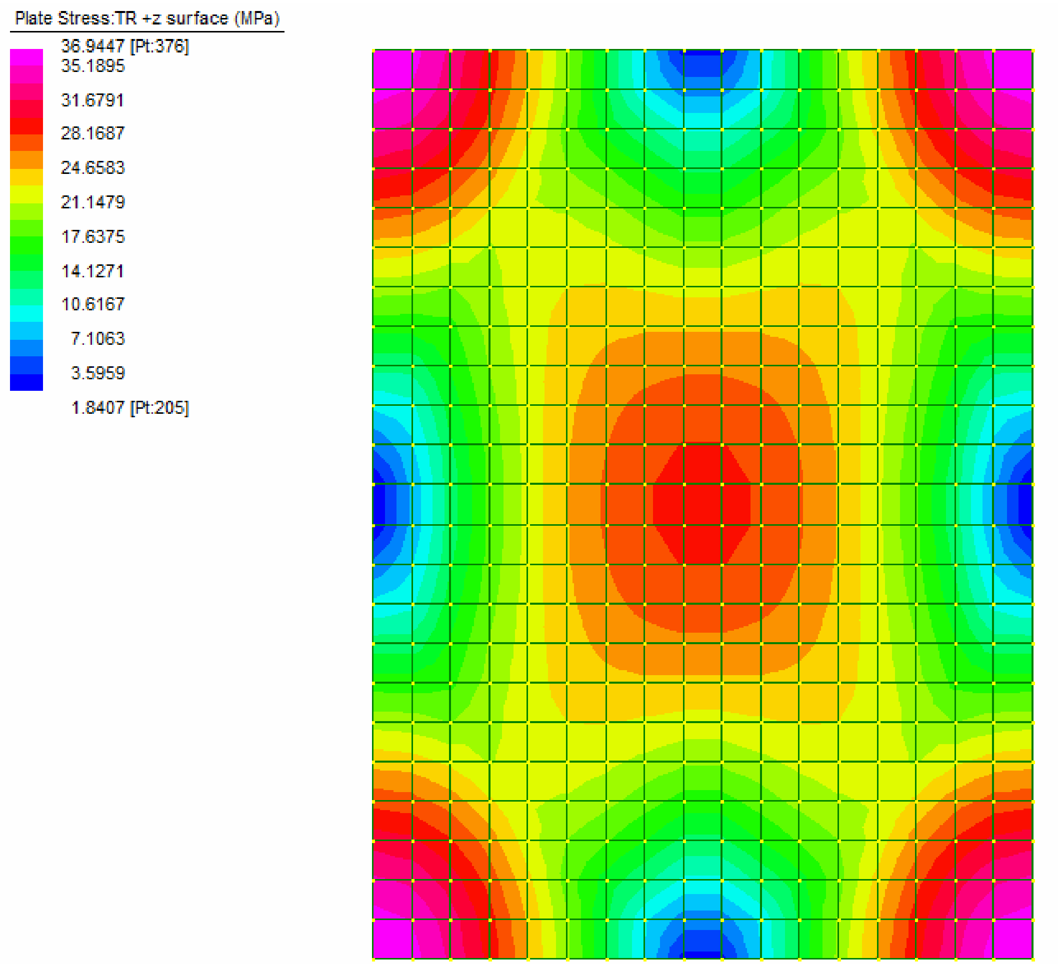


Fig. 25– Stress Diagram of vision glass (Strand 7)

According to AS 1288, the stress limit for Tempered Glass is 49MPa.

From the result shown in the figure 25, Maximum stress = 37MPa, which is smaller than 49MPa. So, the result is accepted.

From the contour stress diagram, the maximum stress is located at four corners of the panel. Also because of the panel was supported by 4 sides, the glass was deformed inward from the centroid when normal pressure force applied on the glass.

D) Impact load calculation:

Since it is a project in Hong Kong, refer to Hong Kong Building (Construction) Regulations, Chapter 123B Regulation 17 Table 3, Imposed loads on protective barriers. Since these two towers were commercial and residential used, so non-crowd impact load was considered at the glass panel. The requirements for this regulation was drafted as follow:

Usage	Uniformly distributed load to be applied at a height of 1.1m above floor level	Uniformly distributed load applied on the infill between floor and top rail	Concentrated load applied on any part of the infill between floor and top rail
	kN/m run	kPa	kN
Areas where crowd load is not expected	0.75	1.0	0.5

I) Loading diagram

The above three different requirements are applied in each panel respectively.

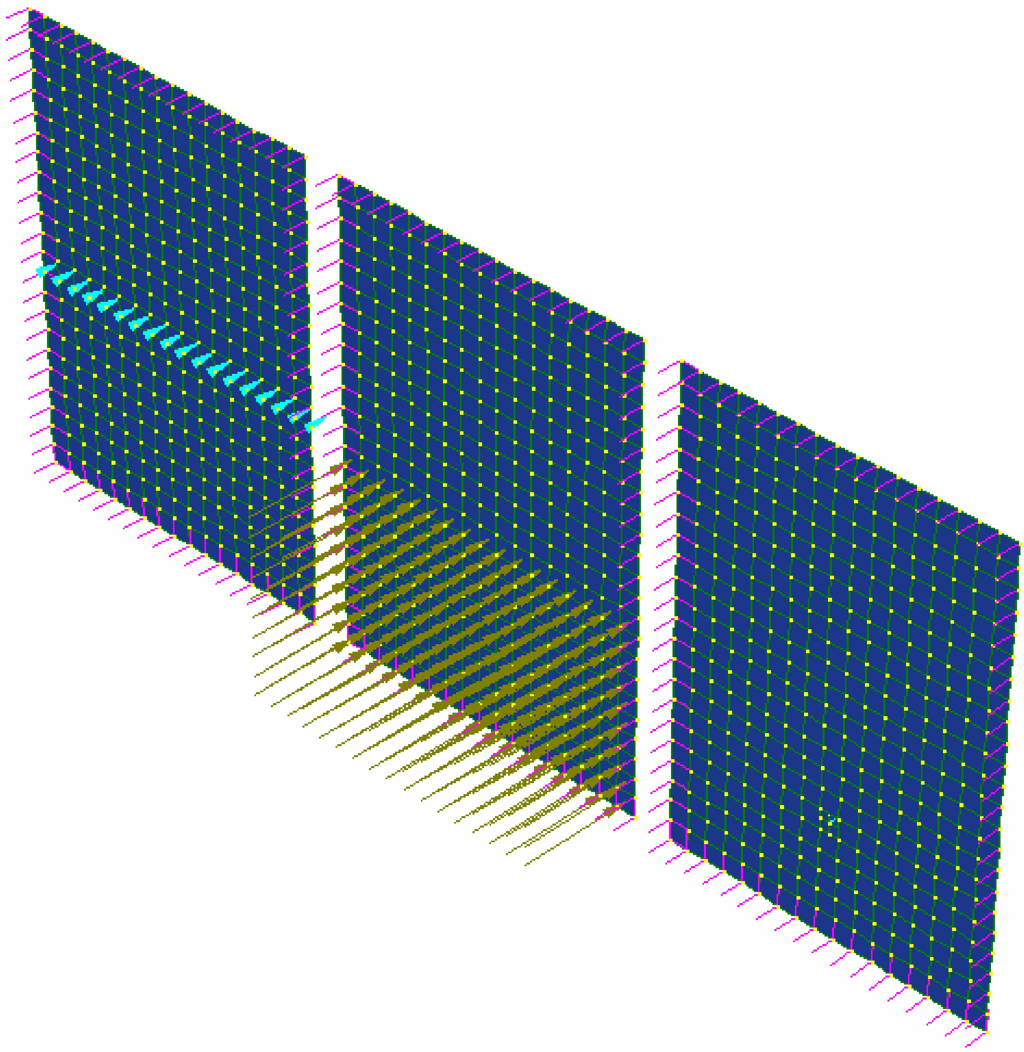


Fig. 26 – Load Diagram of glass during 3 different conditions of impact load

II) Deflection diagram:

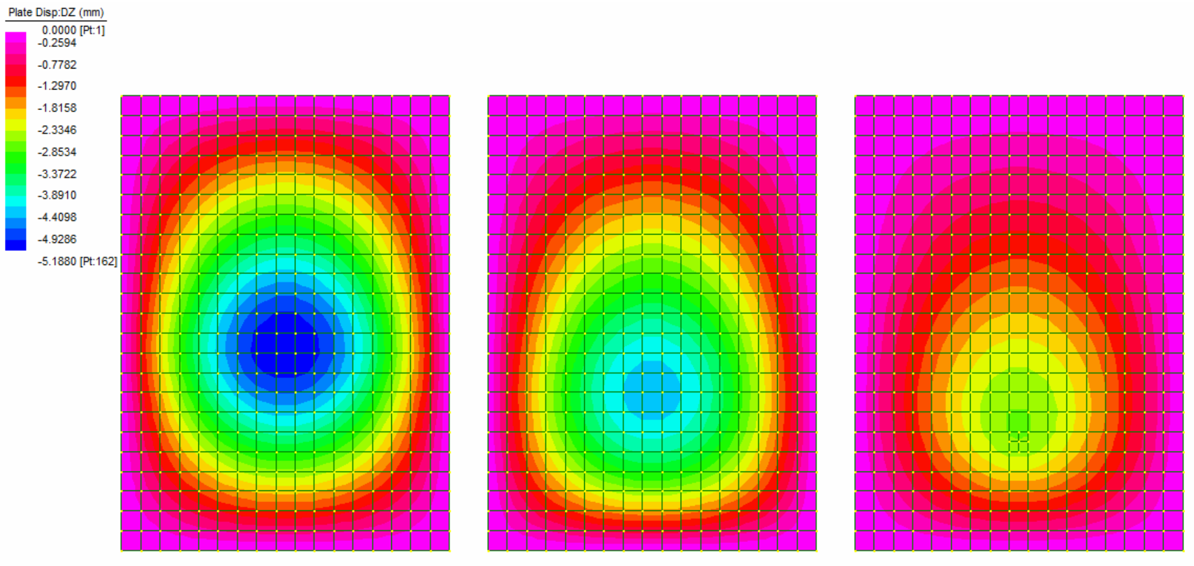


Fig. 27 – Deflection Diagram of glass during 3 different conditions of impact load

From the result shown in the figure 27, Maximum deflection = 5.2mm, which is small than either 28mm and 25mm.

III) Stress diagram:

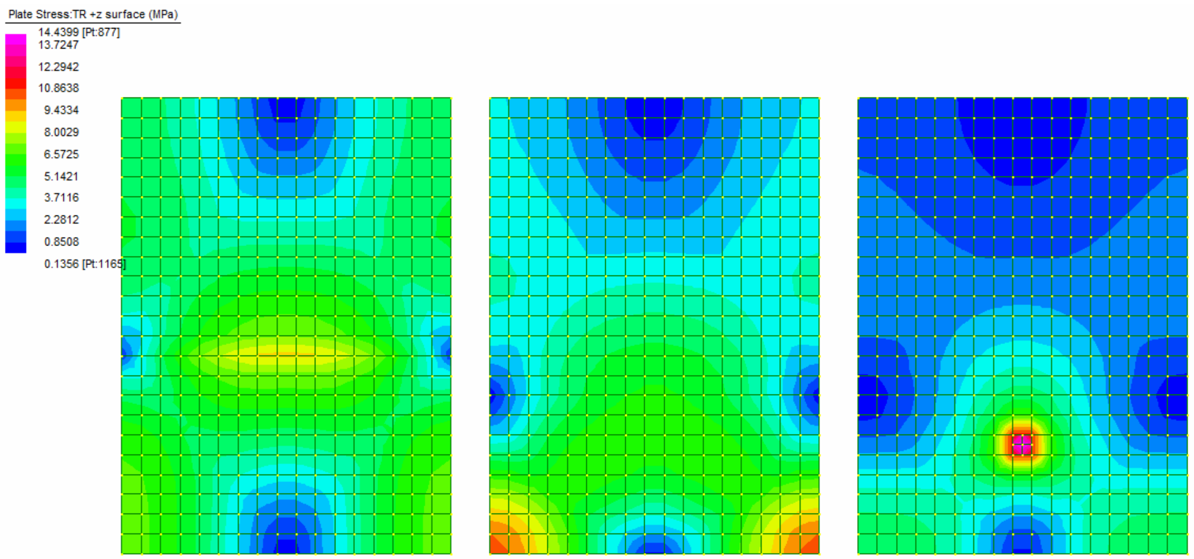


Fig.28 – Stress Diagram of glass during 3 different conditions of impact load

From the result shown in the figure 28, Maximum stress = 14.5MPa, which is smaller than 49MPa.

For vision glass unit, IGU 10mm Tempered Glass + 12mm Air Space + 10mm Tempered Glass was used.

2) Spandrel Glass Design Criteria:

- From the elevation plan, the largest glass plan size is 1700mm x 950mm. From the selection of the Architect, Monolithic with Fully Tempered Glass was used.
- 4-side support of the glass panel by mullions and transoms.
- Glass analysis by linear static of Strand 7.

Loading Diagram:

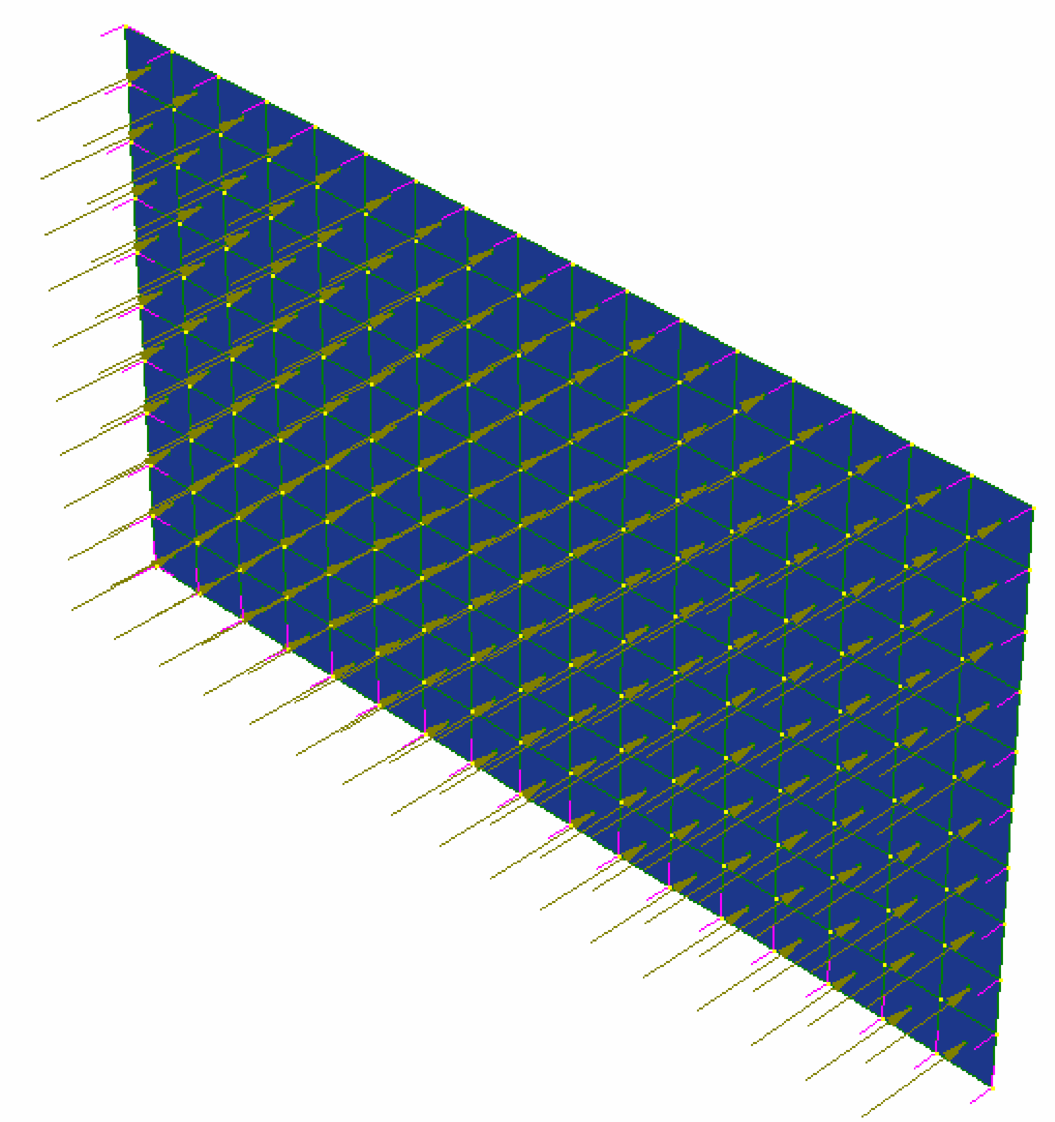


Fig. 29– Load Diagram of spandrel glass (Strand 7)

Loading pressure = 4.62kPa

Glass thickness = 10mm

Glass size = 1700mm x 950mm

Deflection Diagram:

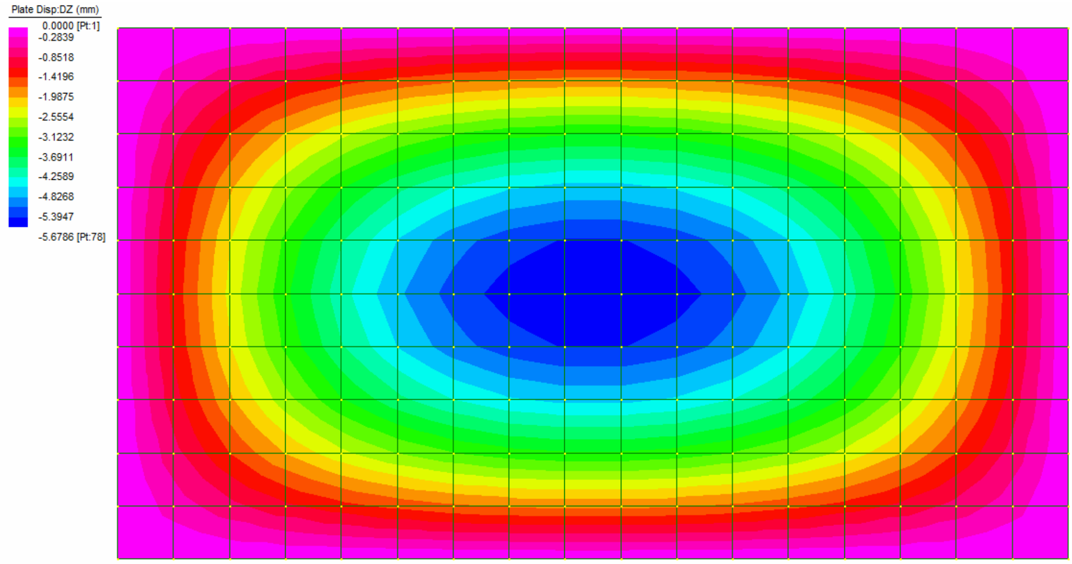


Fig. 30 – Deflection Diagram of spandrel glass (Strand 7)

From the result shown in figure 30, Maximum deflection = 5.7mm, which is small than either 15.8mm and 25mm.

So, the result is accepted.

Stress Diagram:

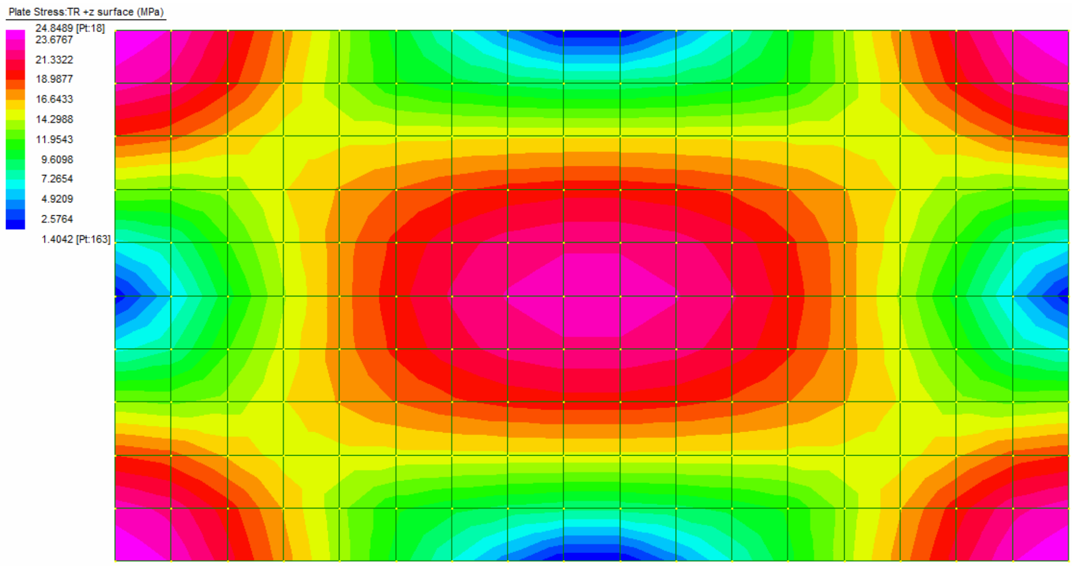


Fig. 31 – Stress Diagram of spandrel glass (Strand 7)

From the result shown in the figure 31, Maximum stress = 25MPa, which is smaller than 49MPa. So, the result is accepted.

For spandrel glass unit, Monolithic 10mm Tempered Glass was used.

5.2.3 Structural modeling

I) Aluminium Mullion design

After analysis of glass properties, the behavior of vertical structure for curtain wall will be analyzed by Structural Analysis software – Space Gass.

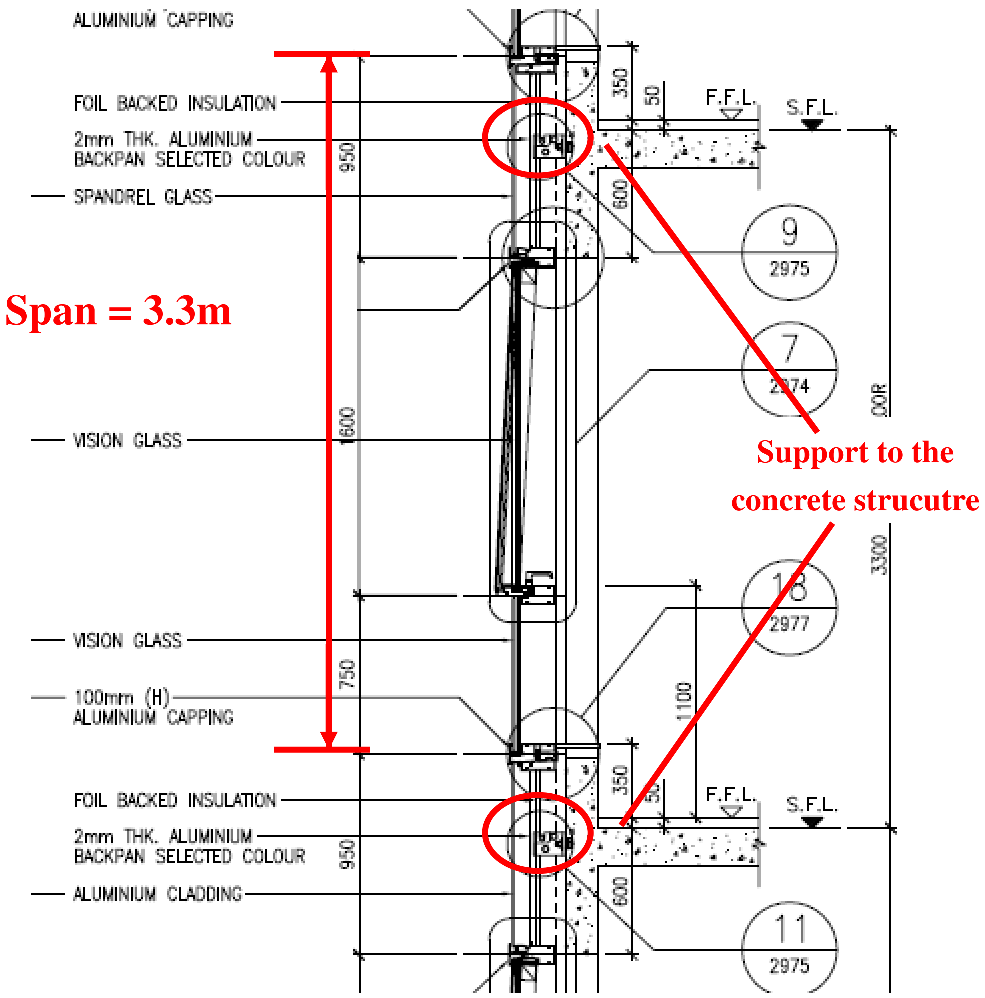


Fig. 32 - Cross section details of the elevation of curtain wall system.

Usually 4 floors of vertical member of curtain wall will be enough for analysis by structural analysis program, refer to figure 33. Since, the support condition of vertical member is similar to the behavior of continuous beam, so the analysis result of 4 floors vertical member is nearly 90% true for actually condition. It is true that full condition selected for modeling, the result will be more accuracy. However, as this case study, the tower contains 60th floor, it will cause more time consuming for whole tower analysis.

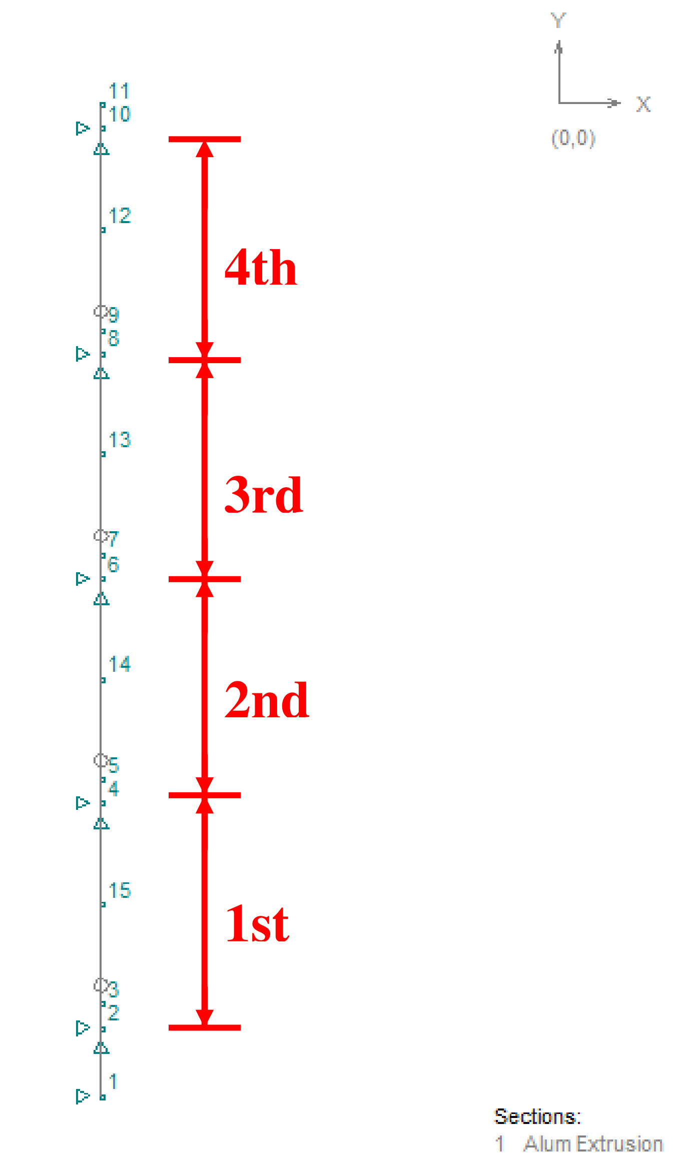


Fig. 33– Space Gass model for mullion with 4 floors

Structural model criteria, refer to figure 33:

- Member between Nodes 1 to 2 is a starter of curtain wall system. It is used for stabilize the whole structure.
- Members between Nodes 3 to 4 is whole mullion for one unitized curtain wall between 2 slab floors. Similar combination for other members
- Stack joint is located in between two whole mullions. Vertical load and moment will be released.

Data Input:

Basically, mullion will take wind loading, the distribution area of wind load are shown as the highlighted portion of the following sketch in figure 34:

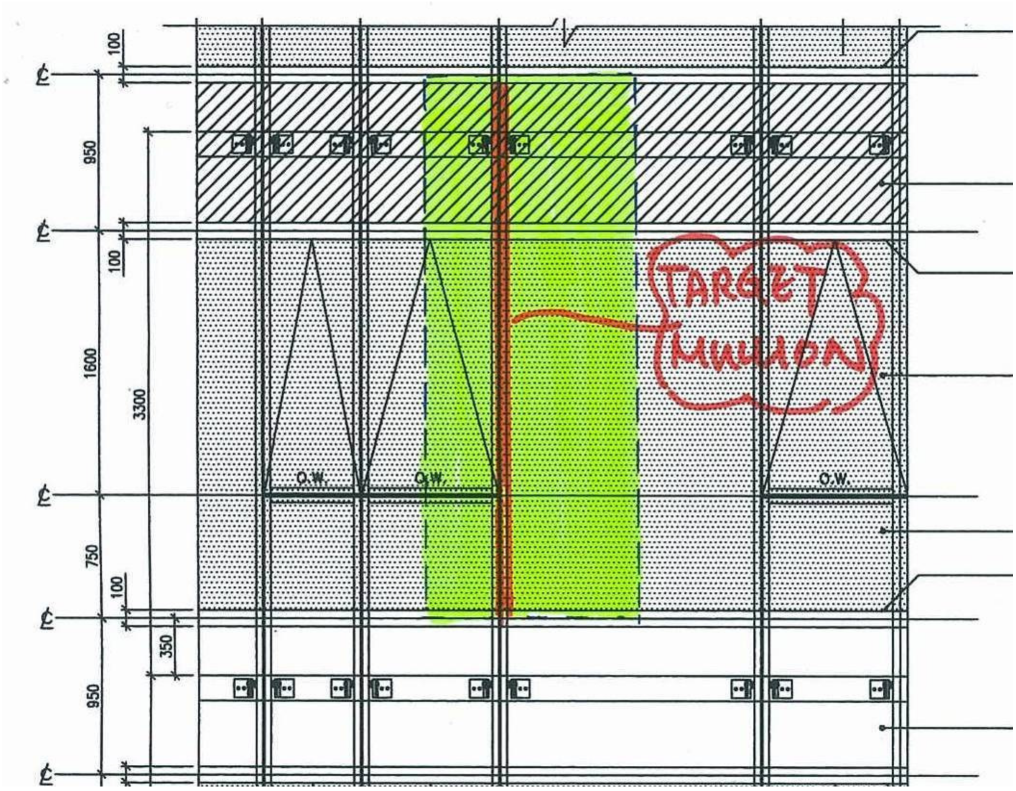


Fig. 34– The most critical distribution of wind load for mullion

a) Node coordinates

Node	X	Y	Z
1	0	0	0
2	0	1000	0
3	0	1350	0
4	0	4300	0
5	0	4650	0
6	0	7600	0
7	0	7950	0
8	0	10900	0
9	0	11250	0
10	0	14200	0
11	0	14550	0
12	0	12725	0
13	0	9425	0
14	0	6125	0
15	0	2825	0

Table 1 – Node coordinates of mullion

b) Node Restraints

Node	Code	Gen	Fx Stiffness	Fy Stiffness	Fz Stiffness	Mx Stiffness	My Stiffness	Mz Stiffness
1	FRDDDR	No	0	0	0	0	0	0
2	FFDDDR	No	0	0	0	0	0	0
4	FFDDDR	No	0	0	0	0	0	0
6	FFDDDR	No	0	0	0	0	0	0
8	FFDDDR	No	0	0	0	0	0	0
10	FFDDDR	No	0	0	0	0	0	0

Table 2 – Node restraints condition of mullion

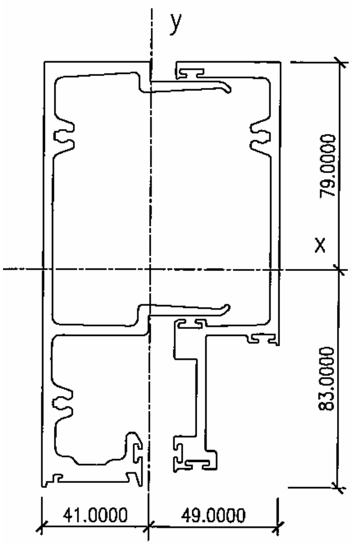
c) Member end release

Memb	Skew Angle	Dir Node	Dir Axis	Member Type	Na	Nb	Sect	Matl	Fixity at Na	Fixity at Nb
1	0	N/A	N/A	Normal	1	2	1	1	FFFFFF	FFFFFF
2	0	N/A	N/A	Normal	2	3	1	1	FFFFFF	FFFFFF
3	0	N/A	N/A	Normal	3	15	1	1	RFFFFR	FFFFFF
4	0	N/A	N/A	Normal	4	5	1	1	FFFFFF	FFFFFF
5	0	N/A	N/A	Normal	5	14	1	1	RFFFFR	FFFFFF
6	0	N/A	N/A	Normal	6	7	1	1	FFFFFF	FFFFFF
7	0	N/A	N/A	Normal	7	13	1	1	RFFFFR	FFFFFF
8	0	N/A	N/A	Normal	8	9	1	1	FFFFFF	FFFFFF
10	0	N/A	N/A	Normal	10	11	1	1	FFFFFF	FFFFFF
11	0	N/A	N/A	Normal	9	12	1	1	RFFFFR	FFFFFF
12	0	N/A	N/A	Normal	13	8	1	1	FFFFFF	FFFFFF
13	0	N/A	N/A	Normal	14	6	1	1	FFFFFF	FFFFFF
14	0	N/A	N/A	Normal	15	4	1	1	FFFFFF	FFFFFF
15	0	N/A	N/A	Normal	3	15	1	1	RFFFFR	FFFFFF
16	0	N/A	N/A	Normal	5	14	1	1	RFFFFR	FFFFFF
17	0	N/A	N/A	Normal	7	13	1	1	RFFFFR	FFFFFF
18	0	N/A	N/A	Normal	12	10	1	1	FFFFFF	FFFFFF
20	0	N/A	N/A	Normal	13	8	1	1	FFFFFF	FFFFFF
21	0	N/A	N/A	Normal	14	6	1	1	FFFFFF	FFFFFF
22	0	N/A	N/A	Normal	15	4	1	1	FFFFFF	FFFFFF

Table 3 – Member end release condition of mullion

d) Section properties

Input of section properties will follow the following mullions design in figure 35.



MASS PROPERTIES (UNIT)	VALUES
Area (mm2) :	2764.8890
Perimeter (mm) :	1367.9708
Bounding Box – X (mm):	–40.5700 to 49.4300
Bounding Box – Y (mm):	–83.3005 to 79.1995
Centroid – X (mm) :	0.0000
Centroid – Y (mm) :	0.0000
Moments of inertia – X (mm4) :	8379601.0445
Moments of inertia – Y (mm4) :	2821450.0272
Product of inertia – XY (mm4) :	991637.9147
Radii of gyration – X (mm) :	55.0520
Radii of gyration – Y (mm) :	31.9446
Principal moments along X–Y (mm4) :	2649829.6118 along [0.1705 0.9854]
Principal moments along Y–X (mm4) :	8551221.4600 along [–0.9854 0.1705]
Elastic Modulus – Zx (mm3):	I / y–max= 100594.7980
Elastic Modulus – Zy (mm3):	J / x–max= 57079.7340

Fig. 35- Cross section and section properties for mullion of curtain wall.

e) Load case

Load Case Titles

1

Case	Title
1	Self weight
2	Wind Load (Pressure)
3	Wind Load (Suction)
11	Combined (Case 1+2)
12	Combined (case 1+3)
21	Case 11 (1.2 Factored)
22	Case 12 (1.2 Factored)

Table 4 – Load case for mullion

Combination Load Cases

11

Case	Primary Load Cases	Multiplying Factors
11	1,2	1.2,1
12	1,3	1.2,1
21	1,2	1.44,1.2
22	1,3	1.44,1.2

Table 5 – Combination load cases summary for mullion

Noted

- Self weight of mullion will be added up 20% for including the weight of transom and glass.
- According to BS8118, Loading factor is 1.2 for aluminium structure.

f) Member distributed force

Case	Memb	Sub	Axes	Units	Start	Finish	Fx Start	Fx Finish
2	1	1	G-Incl	%	0	100	4.069	4.069
2	2	1	G-Incl	%	0	100	4.069	4.069
2	3	1	G-Incl	%	0	100	4.069	4.069
2	4	1	G-Incl	%	0	100	4.069	4.069
2	5	1	G-Incl	%	0	100	4.069	4.069
2	6	1	G-Incl	%	0	100	4.069	4.069
2	7	1	G-Incl	%	0	100	4.069	4.069
2	8	1	G-Incl	%	0	100	4.069	4.069
2	10	1	G-Incl	%	0	100	4.069	4.069
2	11	1	G-Incl	%	0	100	4.069	4.069
2	12	1	G-Incl	%	0	100	4.069	4.069
2	13	1	G-Incl	%	0	100	4.069	4.069
2	14	1	G-Incl	%	0	100	4.069	4.069
2	15	1	G-Incl	%	0	100	4.069	4.069
2	16	1	G-Incl	%	0	100	4.069	4.069
2	17	1	G-Incl	%	0	100	4.069	4.069
2	18	1	G-Incl	%	0	100	4.069	4.069
2	20	1	G-Incl	%	0	100	4.069	4.069
2	21	1	G-Incl	%	0	100	4.069	4.069
2	22	1	G-Incl	%	0	100	4.069	4.069
3	1	1	G-Incl	%	0	100	-5.7	-5.7
3	2	1	G-Incl	%	0	100	-5.7	-5.7
3	3	1	G-Incl	%	0	100	-5.7	-5.7
3	4	1	G-Incl	%	0	100	-5.7	-5.7
3	5	1	G-Incl	%	0	100	-5.7	-5.7
3	6	1	G-Incl	%	0	100	-5.7	-5.7
3	7	1	G-Incl	%	0	100	-5.7	-5.7
3	8	1	G-Incl	%	0	100	-5.7	-5.7
3	10	1	G-Incl	%	0	100	-5.7	-5.7
3	11	1	G-Incl	%	0	100	-5.7	-5.7
3	12	1	G-Incl	%	0	100	-5.7	-5.7
3	13	1	G-Incl	%	0	100	-5.7	-5.7
3	14	1	G-Incl	%	0	100	-5.7	-5.7
3	15	1	G-Incl	%	0	100	-5.7	-5.7
3	16	1	G-Incl	%	0	100	-5.7	-5.7
3	17	1	G-Incl	%	0	100	-5.7	-5.7
3	18	1	G-Incl	%	0	100	-5.7	-5.7
3	20	1	G-Incl	%	0	100	-5.7	-5.7
3	21	1	G-Incl	%	0	100	-5.7	-5.7
3	22	1	G-Incl	%	0	100	-5.7	-5.7

Table 6 –Member distributed force summary for mullion

Result Output:

a) Deflection diagram:

According to the requirement of Hong Kong Building Department, the deflection limit of non-factored load case for Aluminium Structure is Span/180.

For this case, deflection limit = 3300/180 = 18mm

For load case 11

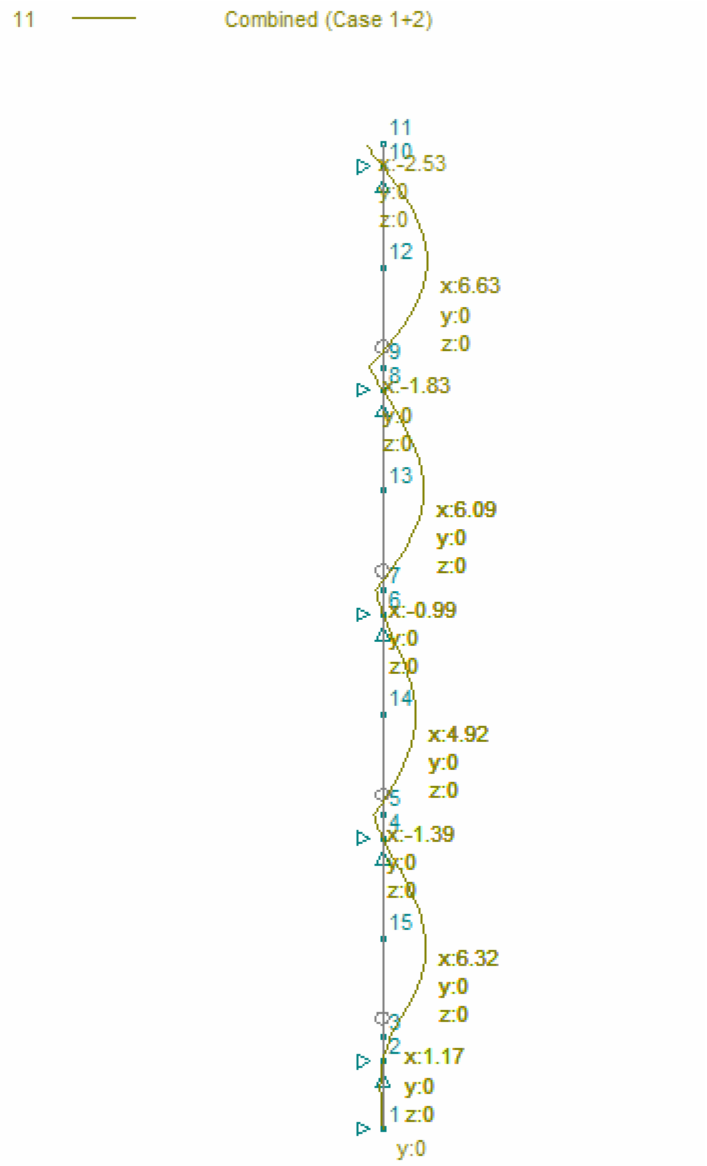


Fig. 36 – Deflection diagram of load case 11 for mullion

From the result shown in figure 36, maximum deflection = 6.63mm < 18mm

So, result is accepted.

For load case 12,

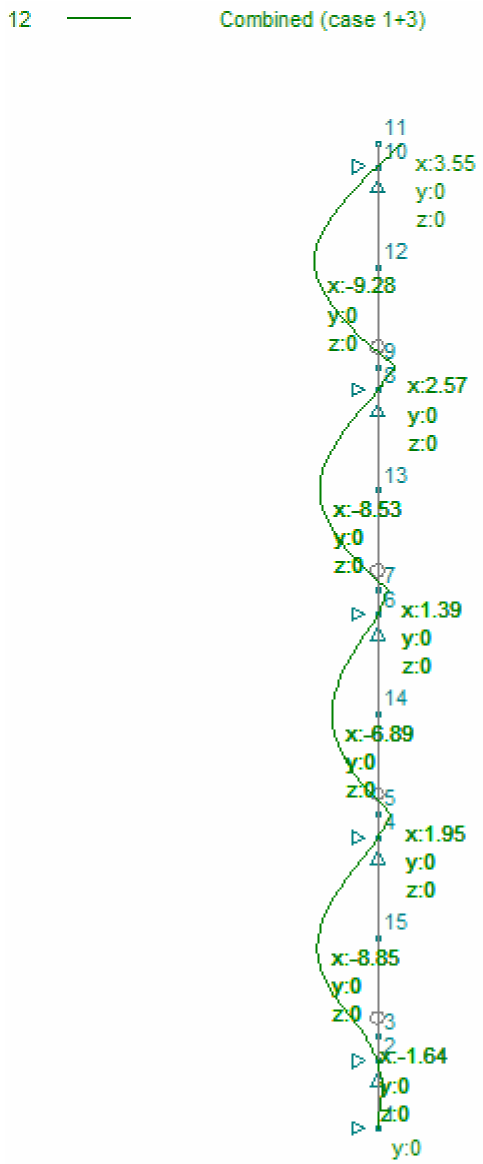


Fig. 37 - Deflection diagram of load case 12 for mullion

From the result shown in figure 37, maximum deflection = 9.28mm < 18mm

So, result is accepted.

From the above deflection diagram for 2 cases in figures 36 and 37, the maximum deflection is located at the last span of the model in load case 12. Load case 12 involves mullion its self-weight and wind suction load, the maximum deflection occurs at load case 12 since the wind suction load is larger than wind pressure load. The deflection pattern shall be similar between each 2 floor slabs.

b) Moment Diagram

For the load case 21,

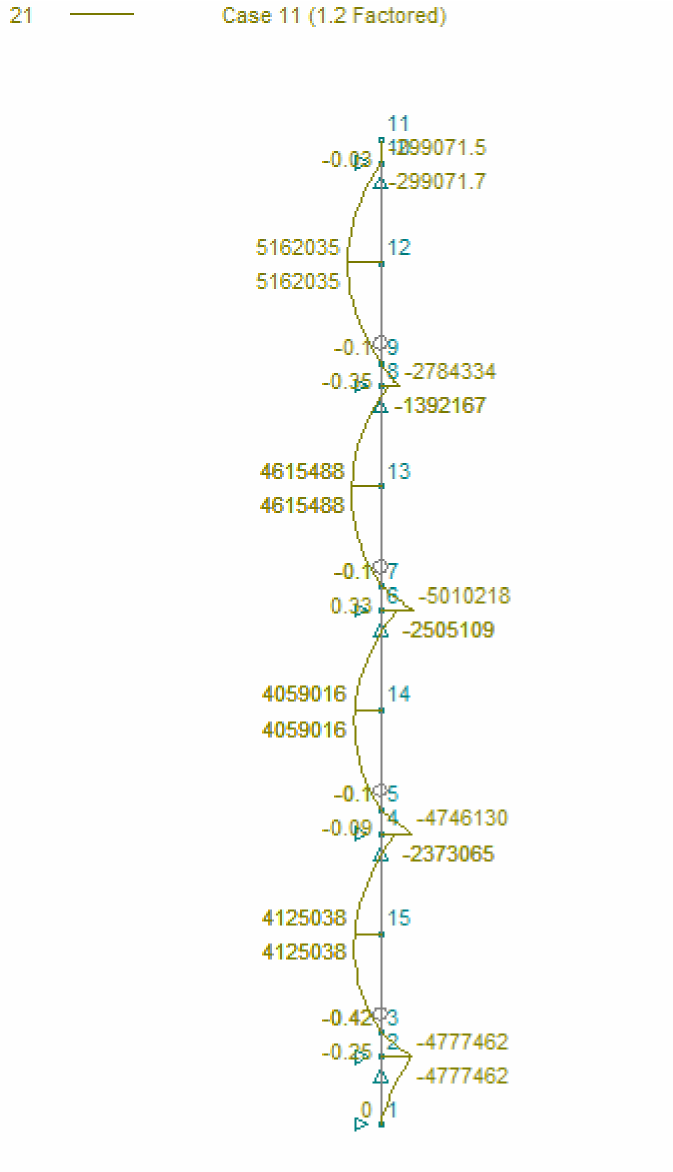


Fig. 38 – Moment diagram of load case 21 for mullion

From the result shown in figure 38, maximum moment = 5.163kNm

Stress = 1.2 x Moment / Elastic modulus

= 1.2 x 5.163 x 10^6 / (100594.798)

= 61.6 MPa < 110MPa (Grade 6063-T5 of Aluminium)

For the load case 22,

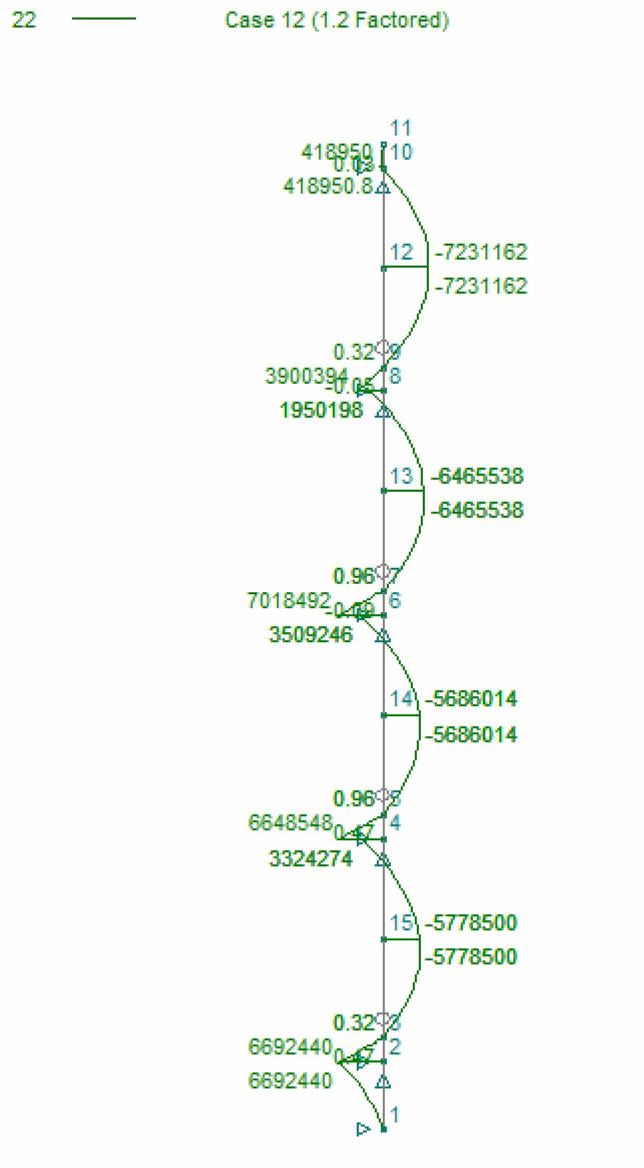


Fig. 39 – Moment diagram of load case 22 for mullion

From the result shown in figure 39, maximum moment = 7.232kNm

Stress = 1.2 x Moment / Elastic modulus

= 1.2 x 7.232 x 10^6 / (100594.798)

= 86.3MPa < 110MPa (Grade 6063-T5 of Aluminium)

From the above moment diagram for 2 cases in figures 38 and 39, the maximum moment is located at the last span of the model in load case 22. Load case 22 involves mullion its self-weight and wind suction load with load factored for aluminium material, the maximum moment occurs at load case 22 since the wind suction load is larger than wind pressure load. The moment pattern shall be similar between each 2 floor slabs, and with zero moment at each stack joint.

Node Reaction

```
Load case 21 (Linear): Case 11 (1.2 Factored)

          X-Axis     Y-Axis     Z-Axis     X-Axis     Y-Axis     Z-Axis
 Node      Force      Force      Force     Moment     Moment     Moment

    1   2336.062      0.000      0.000      0.000      0.000      0.000
    2 -21723.244    142.735      0.000      0.000      0.000      0.000
    4 -30427.979    660.811      0.000      0.000      0.000      0.000
    6 -31272.037    660.811      0.000      0.000      0.000      0.000
    8 -24157.832    660.811      0.000      0.000      0.000      0.000
   10  -9012.490    348.908      0.000      0.000      0.000      0.000

 Load 114257.516  -2474.078      0.000
 Reac **********   2474.078      0.000

Load case 22 (Linear): Case 12 (1.2 Factored)

          X-Axis     Y-Axis     Z-Axis     X-Axis     Y-Axis     Z-Axis
 Node      Force      Force      Force     Moment     Moment     Moment

    1  -3272.439      0.000      0.000      0.000      0.000      0.000
    2  30430.695    142.735      0.000      0.000      0.000      0.000
    4  42624.594    660.811      0.000      0.000      0.000      0.000
    6  43806.980    660.811      0.000      0.000      0.000      0.000
    8  33841.152    660.811      0.000      0.000      0.000      0.000
   10  12625.017    348.908      0.000      0.000      0.000      0.000

 Load **********  -2474.078      0.000
 Reac 160056.000   2474.078      0.000
```

Table 7 – Node reaction result for mullion

Façade Engineer will used the node reactions for fixing support calculation, such as support bracket, anchor bolts, washer, flashing, welding, etc. And the result also used as concrete design by Structural Engineer.

II) Aluminium Transom Design

Transom at stack joint are selected for calculation.

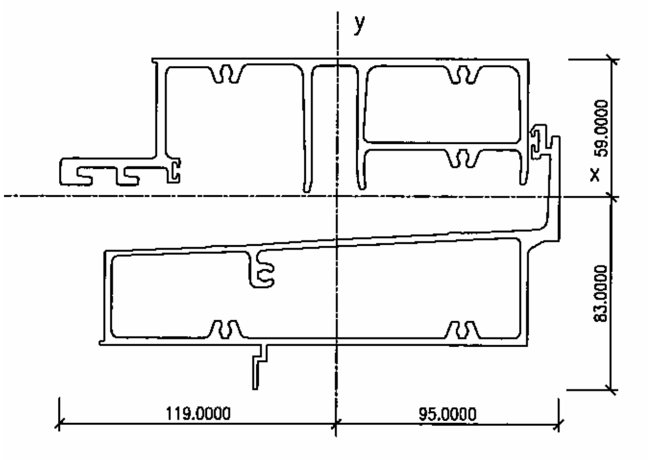
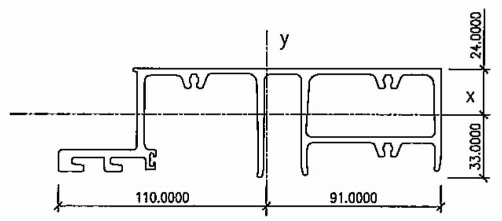


Fig. 40- Cross section of stack joint for transom

Data Input:

- Dead load will only be considered to add on the upper part of the transom only. Dead load included glass weight and transom's self-weight.



MASS PROPERTIES (UNIT)	VALUES
Area (mm^2) :	1913.2120
Perimeter (mm) :	1073.6946
Bounding Box – X (mm):	–109.5665 to 91.4343
Bounding Box – Y (mm):	–33.3385 to 24.0985
Centroid – X (mm) :	0.0000
Centroid – Y (mm) :	0.0000
Moments of inertia – X (mm^4) :	689066.8020
Moments of inertia – Y (mm^4) :	7279934.6530
Product of inertia – XY (mm^4) :	565234.3384
Radii of gyration – X (mm) :	18.9779
Radii of gyration – Y (mm) :	61.6854
Principal moments along X–Y (mm^4) :	640943.5477 along [0.9964 0.0848]
Principal moments along Y–X (mm^4) :	7328057.9074 along [–0.0848 0.9964]
Elastic Modulus – Zx (mm^3):	I / y–max= 20668.8090
Elastic Modulus – Zy (mm^3):	J / x–max= 66443.0514

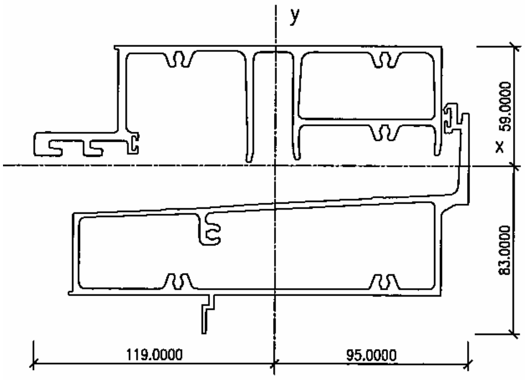
Fig. 41- Section properties for upper part of transom. Dead load will along X-axis.

A spacer called setting block will placed between glass edge and the transom. It will locate at Span/4 from each end of the glass.

Dead load (Point load) at each of 2 setting blocks,

P = (10+10)/1000 x 25 x 2.35 x 1.63 /2 = 0.96kN

Wind load will be carried by whole transom



MASS PROPERTIES (UNIT)	VALUES
Area (mm^2) :	3791.2233
Perimeter (mm) :	2252.7552
Bounding Box – X (mm):	–119.2267 to 95.2733
Bounding Box – Y (mm):	–82.9727 to 59.0273
Centroid – X (mm) :	0.0000
Centroid – Y (mm) :	0.0000
Moments of inertia – X (mm^4) :	6664212.8689
Moments of inertia – Y (mm^4) :	15428601.8068
Product of inertia – XY (mm^4) :	683364.4611
Radii of gyration – X (mm) :	41.9261
Radii of gyration – Y (mm) :	63.7931
Principal moments along X–Y (mm^4) :	6611250.5931 along [0.9970 0.0773]
Principal moments along Y–X (mm^4) :	15481564.0826 along [–0.0773 0.9970]
Elastic Modulus – Zx (mm^3):	I / y–max= 80318.1374
Elastic Modulus – Zy (mm^3):	J / x–max= 129405.6219

Fig. 42 - Section properties of transom. Wind load along Y-axis.

- and the distribution area of wind load are shown as the highlighted portion of the following sketch:

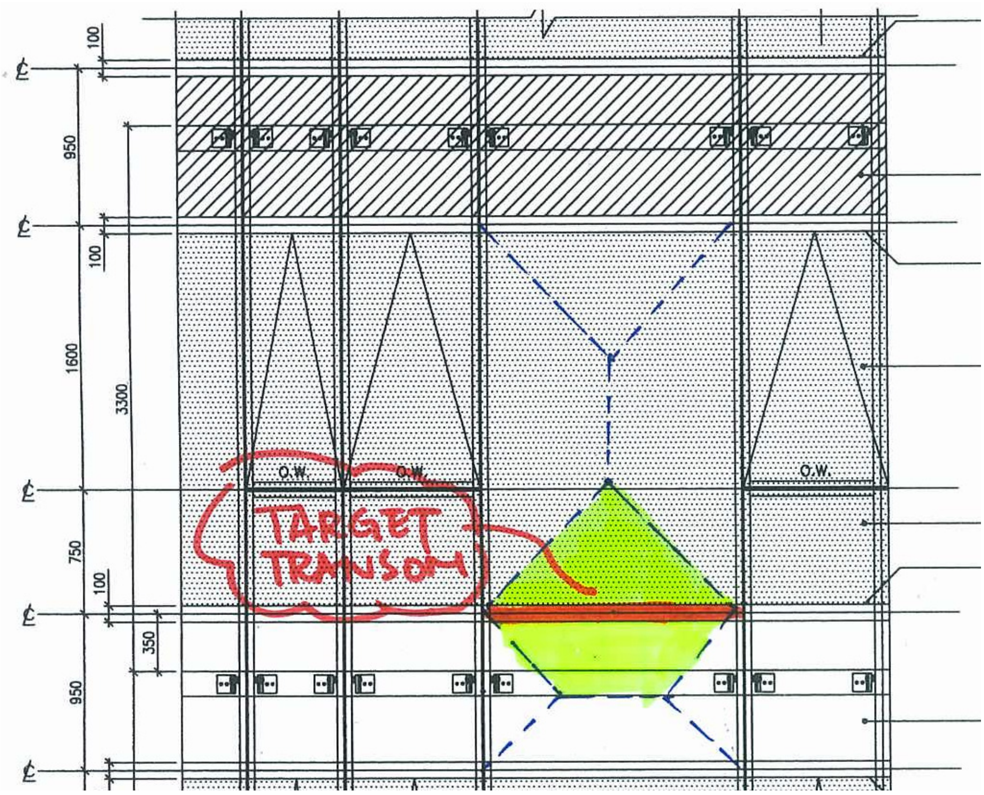


Fig.43 – The most critical distribution of wind load for transom

Node coordinates

Node	X	Y	Z
1	0	0	0
2	408	0	0
3	1222	0	0
4	1630	0	0
5	815	0	0
6	475	0	0
7	1155	0	0

Table 8 – Node coordinates for transom

a) Node Restraints

Node	Code	Gen	Fx Stiffness	Fy Stiffness	Fz Stiffness	Mx Stiffness	My Stiffness	Mz Stiffness
1	FFFRRR	No	0	0	0	0	0	0
4	FFFFRR	No	0	0	0	0	0	0

Table 9 – Node restraints condition for transom

b) Load Case

Case	Title
1	Self weight
2	Dead Load (Glass)
3	Wind Load (Pressure)
4	Wind Load (Suction)
11	Combined load (Case 1+2+3)
12	Combined load (Case 1+2+4)
13	Combined load (Case 1+2)
21	1.2 Factored Load (Case 11)
22	1.2 Factored Load (Case 12)
23	1.2 Factored Load (Case 13)

Table 10 - Load case for Transom

Case	Primary Load Cases	Multiplying Factors
11	1,2,3	1.2,1,1
12	1,2,4	1.2,1,1
13	1,2	1.2,1
21	1,2,3	1.44,1.2,1.2
22	1,2,4	1.44,1.2,1.2
23	1,2	1.44,1.2

Table 11 – Combination load case summary for transom

Noted

- Self weight of mullion will be added up 20% for including the weight of accessories, such as screw, supporting angel, structural sealant, insulator, etc.
- According to BS8118, Loading factor is 1.2 for aluminium structure.

f) Loading table

Member distributed force

Case	Memb	Sub	Axes	Units	Start	Finish	Fx Start	Fx Finish	Fy Start	Fy Finish	Fz Start	Fz Finish
3	1	1	G-Incl	%	0	100	0	0	0	0	0	1.35
3	2	1	G-Incl	%	0	100	0	0	0	0	1.35	1.572236
3	3	1	G-Incl	%	0	100	0	0	0	0	1.35	0
3	4	1	G-Incl	%	0	100	0	0	0	0	2.7	1.572236
3	5	1	G-Incl	%	0	100	0	0	0	0	1.572236	2.7
3	6	1	G-Incl	%	0	100	0	0	0	0	1.572236	1.35
3	1	2	G-Incl	%	0	100	0	0	0	0	0	1.3464
3	2	2	G-Incl	%	0	100	0	0	0	0	1.3464	1.5675
3	3	2	G-Incl	%	0	100	0	0	0	0	1.3464	0
3	4	2	G-Incl	%	0	100	0	0	0	0	1.5675	1.5675
3	5	2	G-Incl	%	0	100	0	0	0	0	1.5675	1.5675
3	6	2	G-Incl	%	0	100	0	0	0	0	1.5675	1.3464
4	1	1	G-Incl	%	0	100	0	0	0	0	0	-1.89
4	2	1	G-Incl	%	0	100	0	0	0	0	-1.89	-2.2
4	3	1	G-Incl	%	0	100	0	0	0	0	-1.89	0
4	4	1	G-Incl	%	0	100	0	0	0	0	-3.77	-2.2
4	5	1	G-Incl	%	0	100	0	0	0	0	-2.2	-3.77
4	6	1	G-Incl	%	0	100	0	0	0	0	-2.2	-1.89
4	1	2	G-Incl	%	0	100	0	0	0	0	0	-1.89
4	2	2	G-Incl	%	0	100	0	0	0	0	-1.89	-2.2
4	3	2	G-Incl	%	0	100	0	0	0	0	-1.89	0
4	4	2	G-Incl	%	0	100	0	0	0	0	-2.2	-2.2
4	5	2	G-Incl	%	0	100	0	0	0	0	-2.2	-2.2
4	6	2	G-Incl	%	0	100	0	0	0	0	-2.2	-1.89

Table 12 – Member distribution force summary for transom

Node load

Case	Node	Fx	Fy	Fz	Mx	My	Mz
2	2	0	-960	0	0	0	0
2	3	0	-960	0	0	0	0

Table 13 – Node load for transom

g) Loading diagram

- Dead Load (Glass)

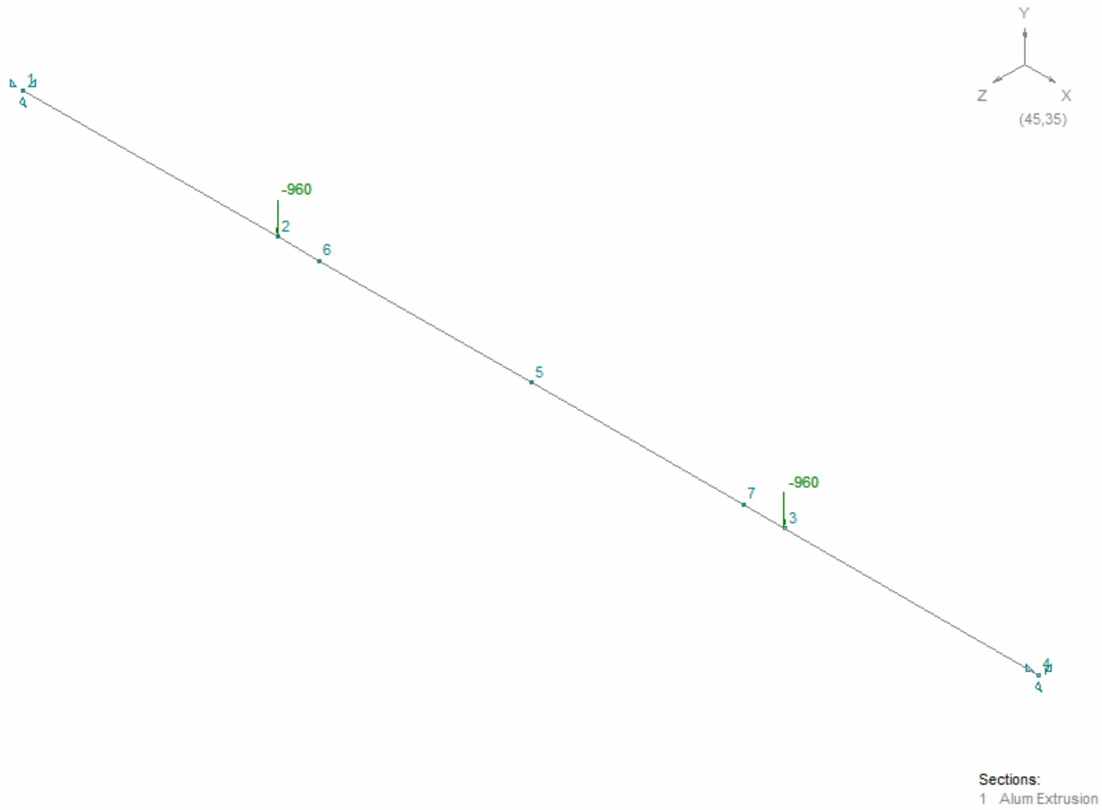


Fig. 44 – Loading diagram (dead load) for transom

- Wind load (Pressure)

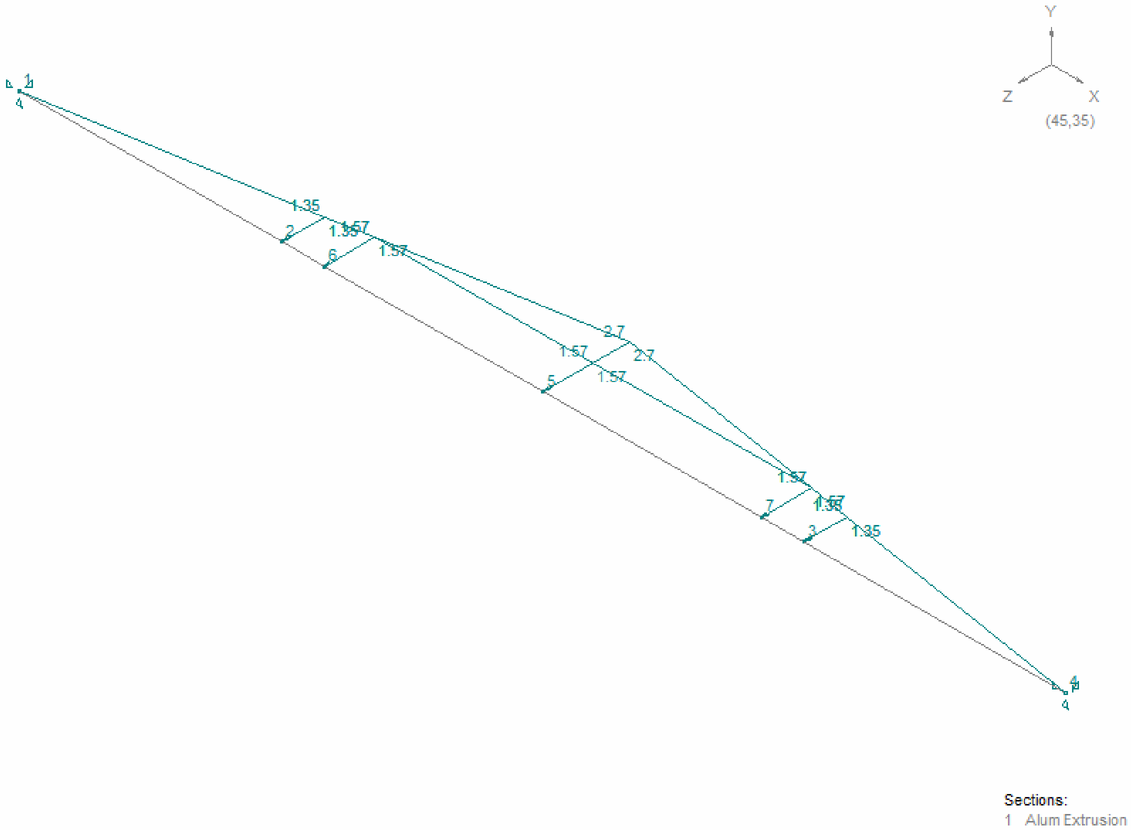


Fig. 45 – Loading diagram (Wind pressure load) for transom

- Wind load (Suction)

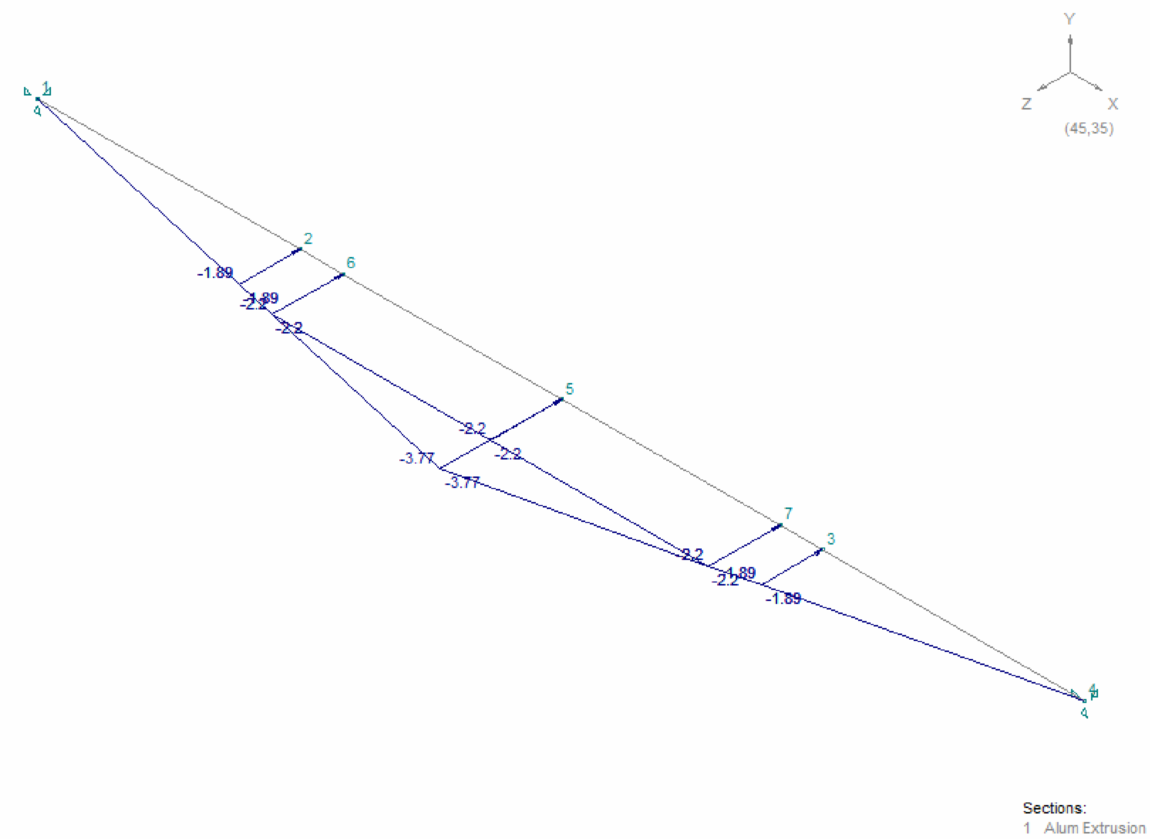


Fig. 46 – Loading diagram (Wind suction load) for transom

Result Output:

a) Deflection diagram:

- For Dead load (Glass + Self weight of Transom) - along Y-axis

According to the requirement of BS8118, the deflection limit of non-factored load case for Aluminium beam is Span/360, where carrying brittle finish.

Deflection limit = 1630/360 = 4.5mm

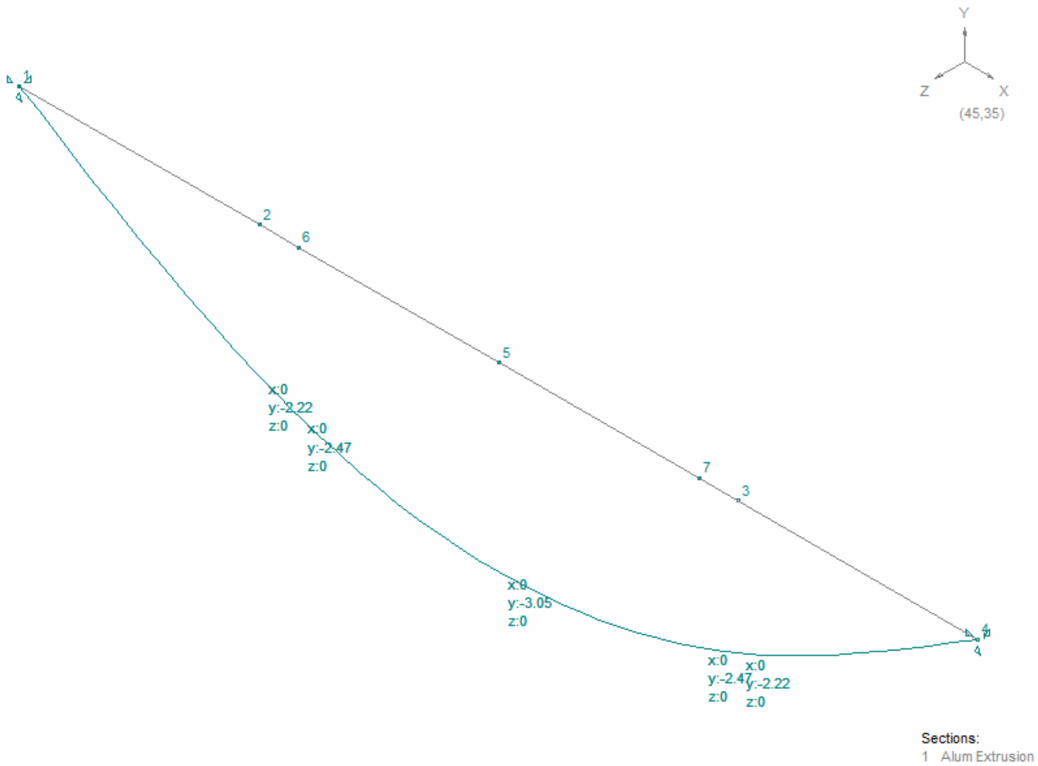


Fig. 47 – Deflection diagram (dead load) for transom

Maximum deflection = 3.05mm <4.5mm

So, result is accepted.

- For Wind Load (Pressure) – along Z-axis

  According to the requirement of Hong Kong Building Department, the deflection limit of non-factored load case for Aluminium Structure is Span/180.

  So, deflection limit = 1630/180 = 9mm

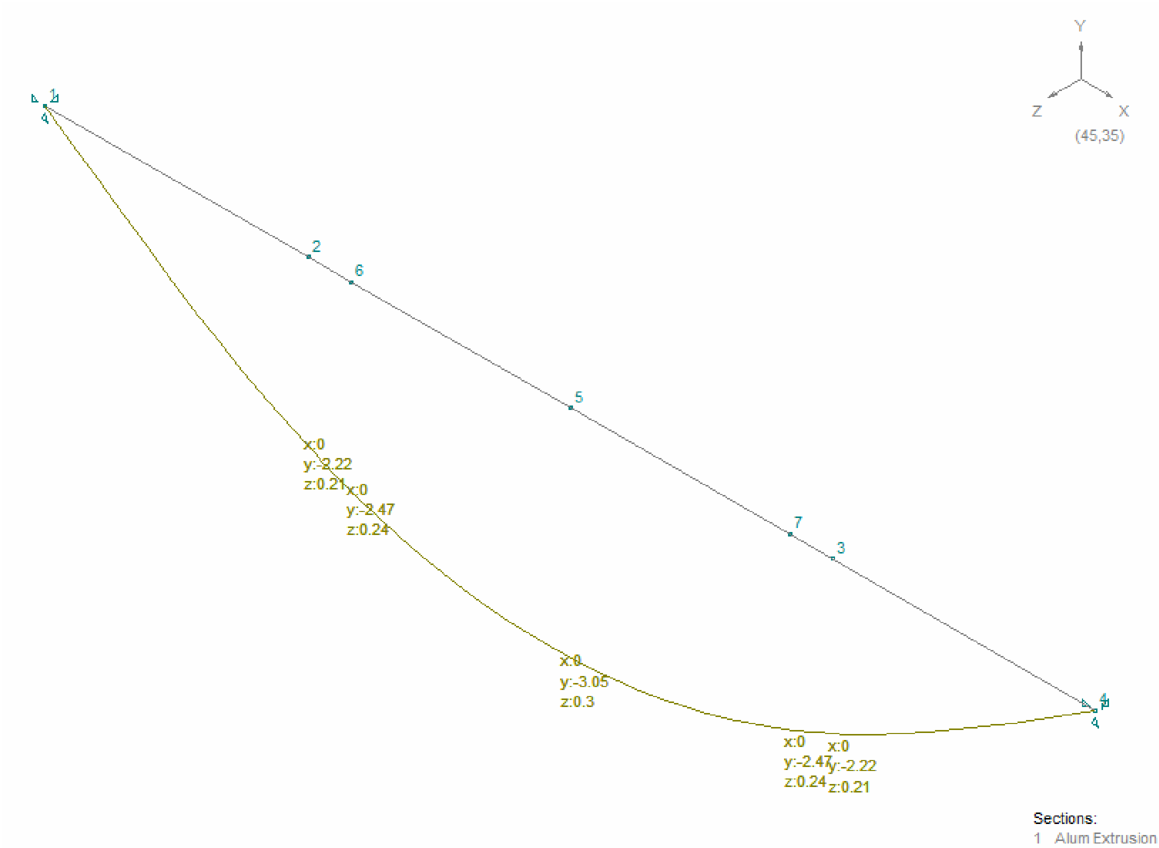


Fig.48 – Deflection diagram (Wind pressure load) for transom

Maximum deflection = 3.05mm < 9mm

Result is accepted.

- For Wind Load (Suction) – along Z-axis

Same as the requirement of wind load (pressure)m

So, deflection limit = 1630/180 = 9mm

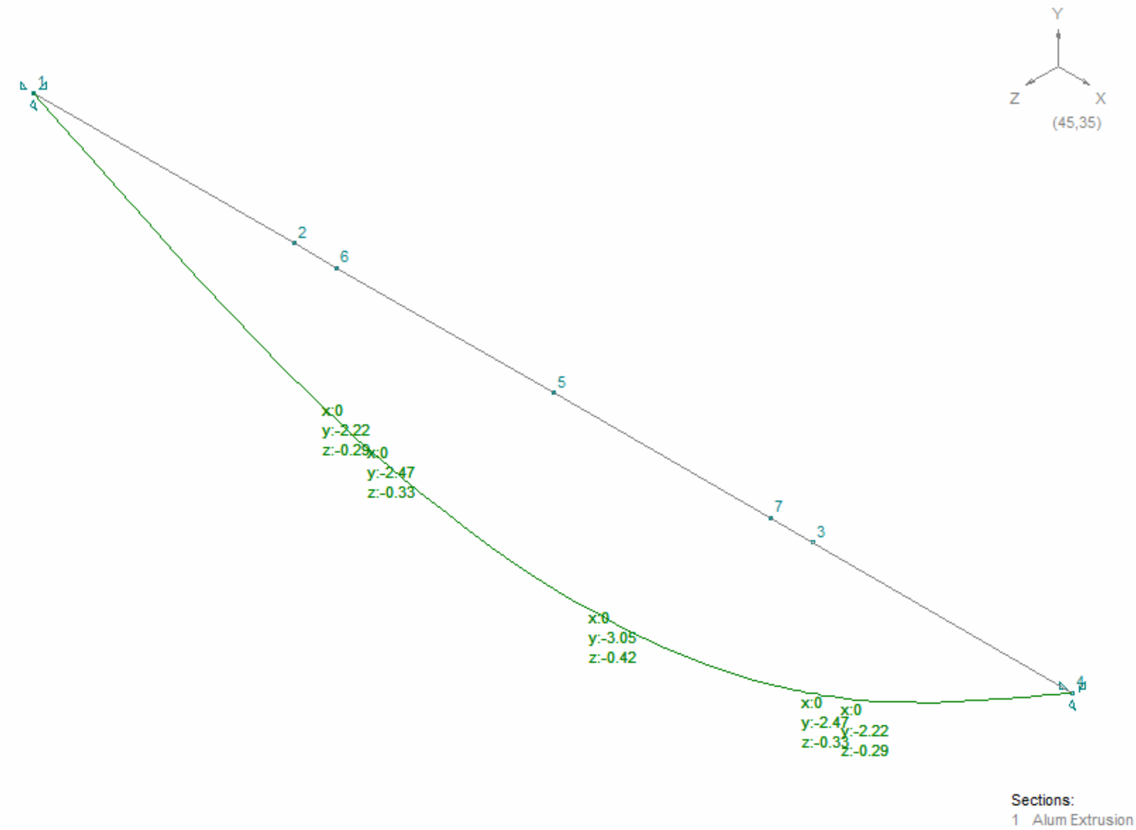


Fig. 49 – Deflection diagram (Wind suction load) for transom

Maximum deflection = 3.05mm < 9mm

Result is accepted.

b) Moment Diagram

For load case 21,

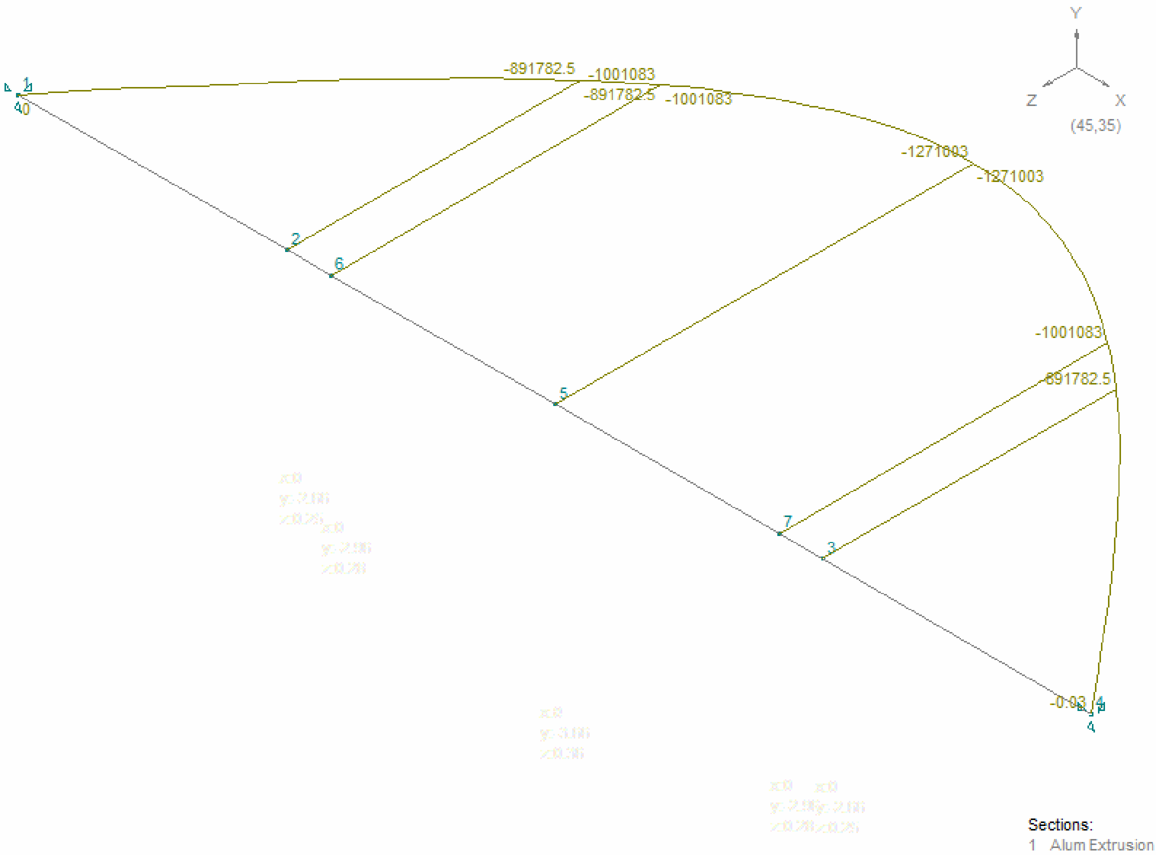


Fig. 50 – Moment diagram (load case 21) for transom

Maximum moment = 1.271kNm

Stress = 1.2 x Moment / Elastic modulus

= 1.2 x 1.271 x 10^6 / (129405.62)

= 11.79MPa < 110MPa (Grade 6063-T5 of Aluminium)

For load case 22,

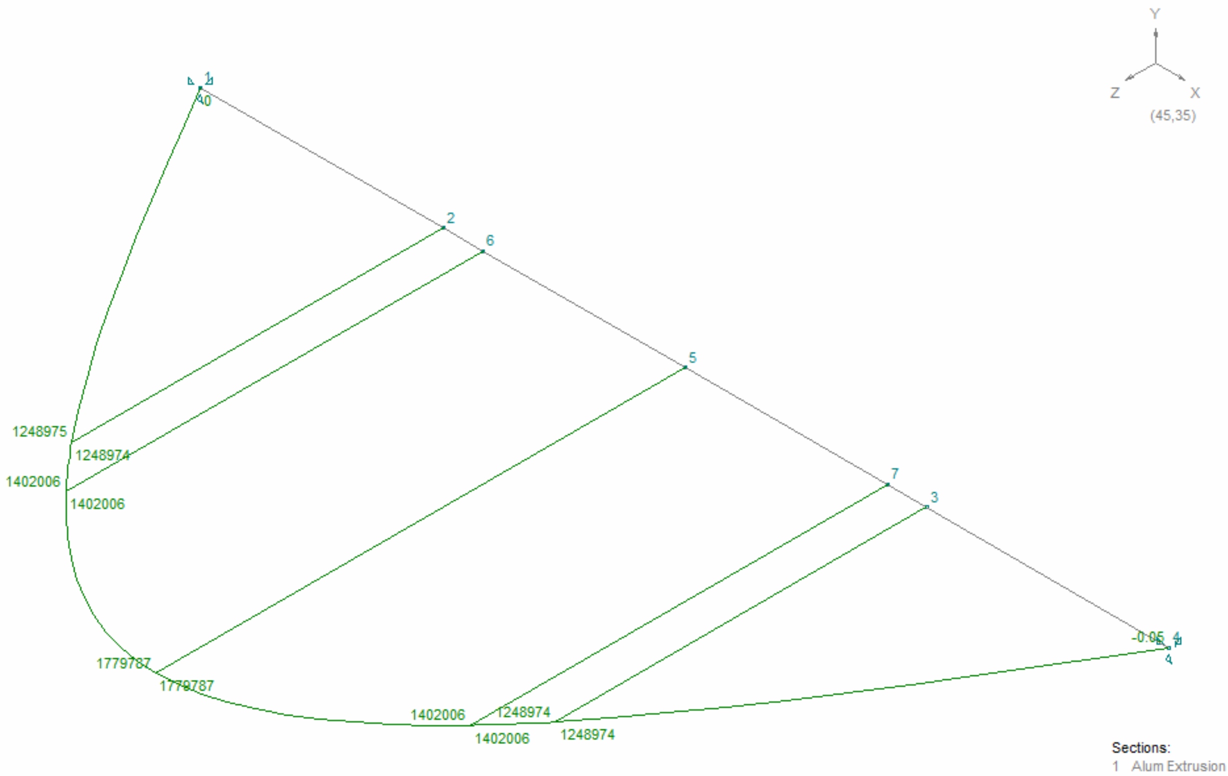


Fig. 51 – Moment diagram (load case 22) for transom

Maximum moment = 1.78kNm

Stress = 1.2 x Moment / Elastic modulus

= 1.2 x 1.78 x 10^6 / (129405.62)

= 16.5MPa < 110MPa (Grade 6063-T5 of Aluminium)

For load case 23,

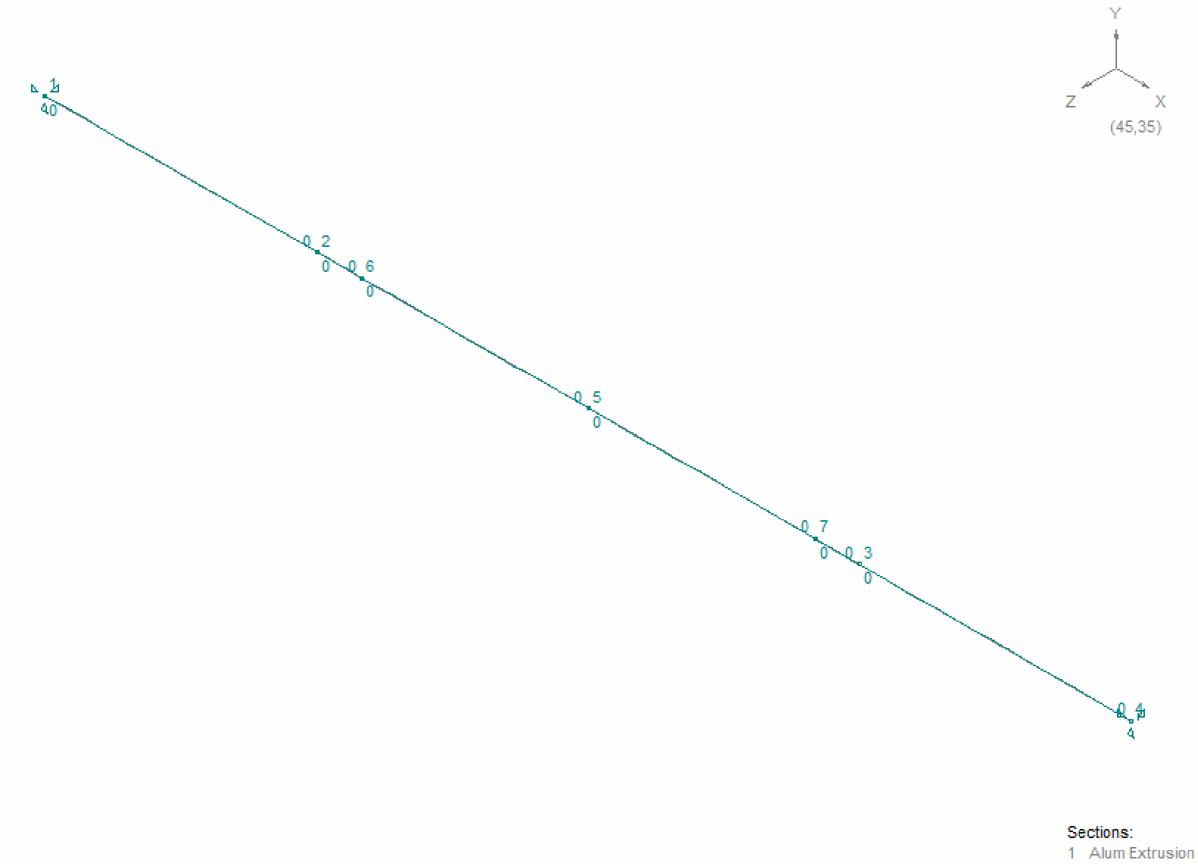


Fig. 52 – Moment diagram (load case 23) for transom

Maximum moment = 0.52kNm

Stress = 1.2 x Moment / Elastic modulus

= 1.2 x 0.52 x 10^6 / (20668.81)

= 30.19MPa < 110MPa (Grade 6063-T5 of Aluminium)

The above is the preliminary checking method for Unitized Curtain Wall system, including Glass, Mullion and Transom. It do have further calculations for whole façade system, such as, bracket, structural sealant bite width, screws and bolts, anchor bolts, and any other nom-typical condition consideration, etc. However, this paper is focus on the discussion of Unitized Curtain Wall, the above calculation is useful for preliminary checking for Unitized Curtain Wall.

CHAPTER 6

CONCULSIONS

6.1 Summary

An investigation into the design and analysis of unitized curtain wall system for high-rise buildings was presented. Design consideration of unitized curtain wall system on structural integrity, provision for movement and weather tightness were discussed. The analyses of unitized curtain wall system by finite element and structural analysis programme were demonstrated.

6.2 Achievement of aims and objectives

This study aimed to discuss the design consideration of unitized curtain wall system for high-rise building and to analysis the curtain wall system with structural and finite element analysis software. The major objectives of this project accompanied with the outcomes of these aims are listed below:

1. Research existing information relating to analysis curtain wall system for high-rise building

The results of an extensive literature review were presented in Chapter 2. However, much of the research conducted was not aimed at structural analysis for curtain wall system.

2. Research on the history and development of curtain wall system

Research information was completed and Chapter 3 discusses the advantages of unitized curtain wall system compared with stick and semi-unitized curtain wall system.

3. Discuss and research on the design consideration of unitized curtain wall system for high-rise building.

The study was completed and presented in Chapter 4. Natural forces and their effects on curtain wall system are discussed. Three major matters on the design concern on unitized curtain wall system were shown. They are structural integrity, provision for movement and weather tightness.

4. Investigation into analysis of unitized curtain wall system for high-rise building

In chapter 5, analysis of unitized curtain wall system in virtual construction project with finite element and structural analysis were demonstrated. The finite element analysis programme – Strand 7 was used to study the behaviour of glass panel. And structural analysis programme – Space Gass was used to study the behaviour of mullion and transom of unitized curtain wall system.

6.3 Conclusions

In the discussion of design consideration for unitized curtain wall system, three major matters which are structural integrity, provision of movement and weather tightness are the chief concern for the system. Prior the design consideration, familiar with the natural effects on curtain wall system is necessary.

The results of finite element analysis on glass indicated that the size and wind pressure governed the deflection and stress behaviour of glass. Glass usually dose not break without a reason. So, analysis the actual condition on glass prior the construction is major issue of Engineer.

The results of structural analysis on the vertical member indicated that nearly 90% of actual condition results can be obtained from only four floors model by structural analysis software. And also, this software was used to obtain the biaxial load analysis results of horizontal members of unitized curtain wall system.

In this study, the unitized curtain wall system was introduced. And analysis of unitized curtain wall with finite element and structural analysis software were demonstrated.

Appendix A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: *Wong Wan Sie, Winxie*

TOPIC: *(title)* Analysis and design of curtain wall systems for high-rise buildings

SUPERVISOR: Dr Stephen Liang

PROJECT AIM: The project aims to analyse the curtain wall system for high-rise building with finite element and structural analysis software.

PROGRAMME: (**Issue A, 27th April, 2007**)

1. Collect information on the analysis and design of curtain walls.

2. Find out the design methods for curtain wall system.

3. Analyse Glass materials (major component of curtain wall) by finite element software (Stand 7).

4. Develop structural model for curtain wall system by structural analysis software (Space Gass)

5. Case study for curtain wall system in some high-rise building projects.

Appendix B

The Code of Practice on Wind Effects in Hong Kong 2004

Reference

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

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So, A.K.W., Lai, B.S.L. and Chan S.L., HKIE Transaction, vol.9, issue 3, December 2002, 'Economical Design of Glass and Aluminum Panels by the Large Deflection Theory'

AAMA (American Architectural Manufacturers Association), 1996, 'Curtain Wall Deisgn Guide Manual'

Reference website

http://www.hku.hk/mech/sbe/case_study/case/hk/pek/info.htm

http://www.legislation.gov.hk

http://www.spacegass.com

http://www.bsi-global.com/en

http://www.astm.org/cgi-bin/SoftCart.exe/index.shtml?E+mystore

http://www.arch.ncku.edu.tw/archit/s25/pages/2.htm