AN INVESTIGATION ON STRESS CONCENTRATION OF POINT-FIXED BOLTED GLASS SYSTEM SUBJECTED TO STATIC LOADING

FARHANAH BINTI FAISAL

SCHOOL OF CIVIL ENGINEERING

UNIVERSITI SAINS MALAYSIA

2018

AN INVESTIGATION ON STRESS CONCENTRATION OF POINT-FIXED GLASS SYSTEM SUBJECTED TO STATIC LOADING

By

FARHANAH BINTI FAISAL

This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering
Universiti Sains Malaysia

June 2018

Appendix A5

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2017/2018

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: An Investigation on Stress Concentration of Point-Fixed Bolted Glass System subjected to Static Loading

Name of Student: Farhanah binti Faisal

I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

Signature:

Approved by:

____

____

(Signature of Supervisor)

Date:

Name of Supervisor: Dr. Mustafasanie M. Yussof

Date:

Approved by:

____

(Signature of Examiner)

Name of Examiner: Assc. Prof. Dr. Choong Kok Keong

Date:

ACKNOWLEDGEMENT

All praise be to ALLAH S.W.T the Almighty, for giving me the blessing, the strength, the chance and endurance to complete this study. After an intensive period of six months, today is the day: writing this note of thanks is the finishing touch on my dissertation. I would like to reflect on the people who have supported and helped me so much throughout this period.

First and foremost, I would like to express my sincere gratitude to my research supervisor, Dr. Mustafasanie M. Yussof for his time, generous guidance, patience and encouragement throughout the whole dissertation project, from which I have learned a lot regarding my title. Without his assistance and dedicated involvement in every step throughout the process, this dissertation would have never been accomplished. Special thanks to my beloved parents, Faisal Abd Rahman and Haizura Shaikh Omar for their sacrifices, full supports and encouragements. Their love, continuous pray and dua' have made me stronger every day on completing this study. You are always there for me. To my lovely sisters, Faiqah and Fasihah, thank you for always keeping me smile and motivated.

I would like to extend my deepest appreciation to all my friends, especially Elly, Sarah, Moreen and Atiqah for kind advice and help throughout my undergraduate studies. Thank you for the four remarkable years of warmth, friendship, and support. Finally, I would like to acknowledge Public Service Department (PSD) which provided the scholarship for my undergraduate studies and all members of the School of Civil Engineering, Universiti Sains Malaysia for all supports.

Thank you very much, everyone!

Penang, Malaysia, May 28, 2018 Farhanah Faisal

ABSTRAK

Fasad kaca struktur dilengkapi bolt mulai berkembang ke tahap penggunaan teknik yang lebih matang dan menjadi sistem fasad lutsinar yang paling tersedia khususnya untuk rumah kedai, laluan pejalan kaki dan kawasan lobi dalam bangunan. Sistem fasad kaca titik tetap, juga dikenali sebagai sistem kaca labah-labah adalah sangat terkenal dan dianggap pilihan fasad yang lebih elegan berbanding sistem fasad kaca berbingkai. Sistem ini ditetapkan pada struktur sokongan menggunakan pemasangan bolt istimewa dan struktur lengan labah-labah yang memerlukan panel kaca didrill dan tempered. Akibatnya, kaca menjadi rapuh terutamanya di kawasan berlakunya tekanan puncak apabila daya dikenakan. Oleh itu, taburan tekanan terhadap sistem kaca berbolt titik tetap yang dikenakan beban statik dikaji berasaskan model berangka dan analisis parametrik. Model berangka dibina mengikut spesifikasi yang dinyatakan dalam projek penyelidikan yang lepas, dilaksanakan menggunakan perisian Abaqus dan dikenakan beban mampatan semasa ujian lenturan tiga titik. Model disahkan dengan membandingkan keputusan eksperimen yang lepas dengan keputusan berangka. Taburan tekanan terhadap panel kaca dianalisis melalui analisis unsur terhingga bukan linear. Pengaruh bilangan sambungan bolt, jarak lubang dari tepi panel, ruang di antara dua lubang bolt berturut-turut, diameter lubang sambungan bolt, susunan sambungan bolt dan ketebalan panel kaca terhadap taburan tekanan boleh ditentukan melalui kajian parametrik. Peningkatan bilangan sambungan bolt, jarak lubang dari tepi panel, diameter lubang sambungan bolt dan ketebalan panel kaca serta susunan sambungan bolt berbentuk berlian akan membawa kesan positif terhadap tegasan principal maksimum.

ABSTRACT

Bolted structural glass facades have evolved to the point where the technique appears to have matured and become the most transparent facade system available mainly for storefront, walkways and lobby areas in buildings. The point fixed glass façade system (PFGFS), also known as a spider glass system, is popular and considered to be a more elegant façade option compared to the framed glass façade system. The system is fixed to the support structure using special bolt fittings and structural spider arms, which implies that the glass must be drilled and tempered. Consequently, the glass is significantly weakened exactly at the position where peak stresses occur when forces are applied. In this research, the stress distribution on point-fixed bolted glass system subjected to static loading are investigated by means of numerical modelling and parametric analyses. A numerical model was constructed according to the specifications specified in past research project, implemented using ABAQUS software and subjected to a compressive load during three points bending test. The model was validated by comparing the past experimental results with the numerical results. By means of non-linear finite element analyses, the stress distribution of the glass panel has been investigated. The influence of the number of connectors, hole-to-edge distance, spacing of the bolt connections, hole diameter, arrangement of connectors and thickness of glass pane on stress distribution were determined through the parametric study. Increasing the number of bolts, the hole-to-edge distance, the bolt hole diameter and the glass thickness as well as the diamond pattern of bolts arrangement, have shown the positive effect on the maximum principal stress.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Arrangement of Connectors
AESS	Architecturally Exposed Structural Steel
BC	Before Christ
CE	Common Era
ED	Edge Distance
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
GSA	Glass Support Attachment
GT	Glass Thickness
HSFG	High Strength Friction Grip
HD	Hole Diameter
IGUs	Insulating Glass Units
LEFM	Linear Elastic Fracture Mechanics
NiS	Nickel Sulfide
PFGFS	Point Fixed Glass Façade System
PSG	Point Supported Glass
PVB	Polyvinyl Butyral
SC	Spacing of Connectors
SGF	Structural Glass Façade
SSG	Structural Sealant Glazing

CHAPTER 1

INTRODUCTION

1.1 Background

Structural glass facade is an integration of a glass system type and an exposed structural system acted as the spanning element supporting the façade. The technology is suitable for longer spanning applications where aluminium extrusion cannot become primary spanning member. Structural glass façade aims for high transparency as design objective. Structural system designs with minimized component profiles were desired to further enhance the transparency of the façade. Frameless glazing system, commonly referred to as point-fixed or point-supported system which comprises of glass, fitting and support structure is most frequently used in structural glass façades. The frameless glazing is emerging as an optical lightness material which offers uninterrupted visual of surroundings and bright working environment with more light and a greater feeling of space. The glazing panels are fixed to the substructure at the corners of the panels in both bolted and patched assembly. In contrast to the principle behind the design of the fittings in patch plate point glazed envelopes where friction developed between the glass interfaces that are produced by the applied pressure, the bolted assembly point-fixed glazed envelopes are connected to support structure via fastening.

In bolted assembly systems, the glass panels are provided with holes at corners and the connection bracket is fastened to the glass through these holes by special bolt fittings and structural spider arms. Figure 1.1 shows some examples of point-fixed glass façade systems. Load bearing capacity of façade systems is often limited by the high stresses around the bolt holes confirmed by the published research related to the strength of bolted connections in glass structural system (Ramm and Burmeister, 1997). Connection assemblies for the glass façade must be designed to prevent high-stress concentration at the hole position and resist wind loading, seismic loads, thermal and load movements. The entire weight of the glazing panels is transferred to the connection bracket through the fixing bolts, thus it is necessary to provide a certain level of flexibility in the connection bolts especially with respect to rotation. Physical and geometrical properties of the members and the bolt influence the strength of the bolt connection. Member properties such as plate thickness and bolt properties include diameter, number and arrangement of bolts. Furthermore, connection geometry, more specifically the end and edge distances, e_1 and e_2, the pitch, p_1 and the gauge, p_2 of bolts are used to determine both edge and end effects of edge and corner connection. Many past research findings have shown these properties to have significant effect to the distribution of stress around the bolt holes. Hence, the behaviour of bolted connections of point-fixed glass façade systems needs to be investigated and understood.

Figure 1.1: Examples of point supported structural glass panels (Bedon and Amadio, 2016)

1.2 Problem Statement

Drilling operations expose the glass elements to environmental factors, and the high contact stresses between the bolt and the hole lead to localized delamination, decreasing the joint strength. The existence of holes in a plate causes a geometrical discontinuity and a disruption of the stress field, and, as a consequence, stress concentrations occur in the region of the holes. The magnitude of the stresses increases with the applied load until fracture initiates at the edge of the bolt hole, where the maximum stress concentration develops. These high values of stress in the vicinity of the hole cause damage during loading prior to ultimate failure. Glass failure may occur very locally by the bearing of a bolt on the surface of the bolt hole through the plate (punching shear), or in an overall mode along a path whose position is determined by the positions of several holes and the actions transferred by the plate. Local surface damages that occur due to processing of holes and edges can lead to a reduction of the strength. Considering point supported glazing, examination of the holes is especially important because, besides possible surface defects, additional stress concentrations in these areas can cause a failure (Maniatis, 2006).

Design of the structural connections in glass is as important as the design of the glass panel itself and is crucial for optimum utilization in the load-bearing glass structures. Several issues with respect to the member and bolt properties such as plate thickness; number, arrangement, geometric and spacing of bolt connection; diameter and position of the hole govern the load capacity of the glass structure and stress distribution around the holes. Therefore, investigation on these factors are needed to verify the strength effects and to formulate a usable design method for the efficient design of bolted connection in structural glass systems.

From the FE numerical and parametric study, the following questions could be answered:

a) Where are the occurrence location of maximum principal tensile stresses when analysing the principal tensile stresses in the direction of the compressive force?

b) What are the influencing parameters that contribute to the distribution of stress around the bolted connection?

c) What are the effects of these parameters on the strength performance of the glass pane supported by bolted point-fixings under static loading?

1.3 Objectives

1. To study the distribution of stress on point-fixed bolted glass system subjected to static loading.
2. To investigate the effect of geometrical properties of point-fixed bolted glass on the distribution of stress around the bolted connection.

1.4 Scope of Work

The scope of work of this study was to develop methodologies for finite element numerical investigation of point-fixed glass system. First, finite element numerical models were developed in ABAQUS software to properly reproduce the mechanical behaviour of point fixed bolted connectors. For verification of the validity of the analytical models, numerical results were compared to existing experimental data derived from past final year project done by Zain (2015). In addition, the distribution of stress in point-fixed bolted glass system subjected to static loading was also studied in this first part. As the second part of the study, the use of this point-supported connection model was subsequently extended to the optimisation of bolted connections by carrying out a parametric study. Specifically, the study attempted to investigate the effect of geometrical properties of point-fixed bolted glass on the distribution of stress around the bolted connection. The validated finite-element modelling approach was then extended to a wide set of geometrical configurations of practical interest, e.g. by varying the geometrical properties of the glass panels as well as the geometrical features of the point supported connectors. By means of a parametric study on this numerical model, the effects of several parameters, such as plate thickness, geometric and spacing of bolt connection, number and arrangement of bolt connections, diameter and position of the holes were investigated. The purpose of numerical simulation was to avoid tedious experimental work of subjecting the glass panels to static loading using different geometrical properties of point supported connectors. In view of further mock-up experiments and full-scale tests, it is expected that the current outcomes could represent a strong theoretical background for the implementation of minimum connection design recommendations and rules for practical use in point-fixed glass system.

1.5 Dissertation Outline

This thesis is structured in five chapters as well as appendices in which attempt has been made to present the work carried out on the subject consistent with the development of the topic concerned. Each thesis contribution is presented in a separate, self-contained chapter.

Chapter 1 is the introduction to this study. The first chapter introduces the background of the study and explains the broad structure of the thesis in term of problem statement, objectives and scope of work.

Chapter 2 is the literature review. The second chapter mainly deals with some of the previous studies related to this research work.

Chapter 3 is the methodology. The third chapter describes in detail the approach used to carry out the research through finite-element numerical investigation. The finite-element model of the point-fixed glass system subjected to static loading is developed using ABAQUS software. Moreover, the preliminary finite-element validation of the point supported connection model is shown in this chapter.

Chapter 4 is result and discussion. The fourth chapter reports the results obtained from the finite-element parametric study.

Chapter 5 is the conclusion and recommendation. The fifth chapter concludes the work based on the objectives of the study and gives the relevant recommendations. In addition, this chapter addresses some open issues and outlines possible directions for further research.

1.6 Expected Outcome

1. Validation of finite element model of the point supported connection model by comparison on the existing experimental data derived from past research project (Rosnita, 2016).
2. The effect of geometrical properties of bolt and glass toward distribution and propagation of stresses within the vicinity of bolted connection through finite element parametric study.

1.7 The Importance and Benefits of the Research

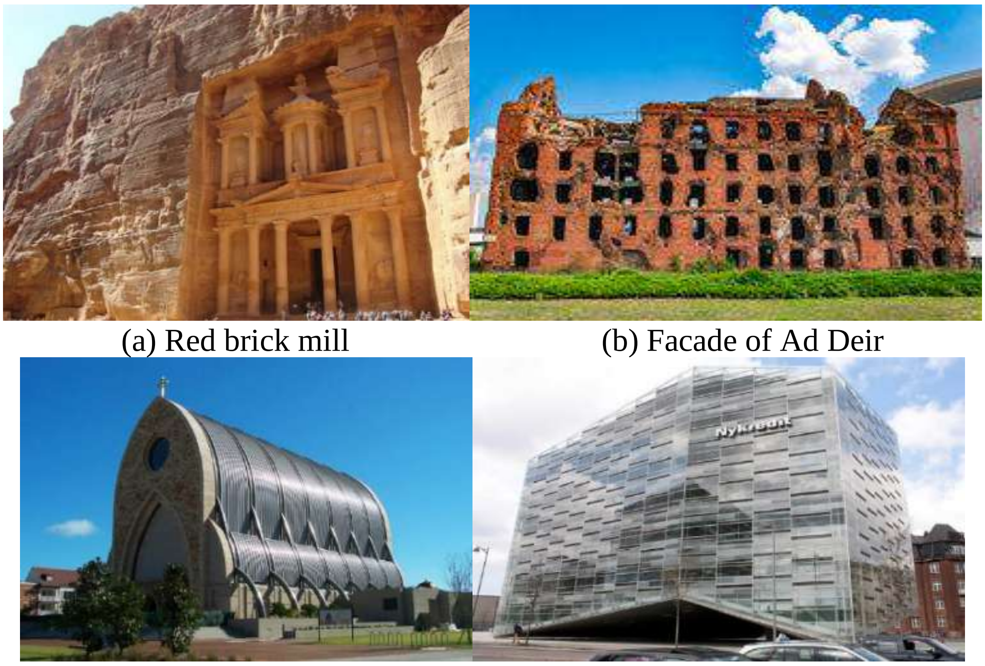
It is known that maximum tensile stress often occurs close to the holes, however, it is rarely possible to determine the stress distribution around the bolt holes by using simple equation or charts. Therefore, finite element modelling is carried out in this study by implementing two-dimensional modelling framework using ABAQUS CAE Version 6.13 software package. The associated finite element analysis is used to analyse conventional connections and subsequently to optimise these connections by varying both the geometry of the bolted connection and the materials used.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Façade systems comprise the structural elements that provide lateral and vertical resistance to wind and other actions, and the building envelope elements that provide the weather resistance and thermal, acoustic and fire resisting properties. Façades and building envelopes which form the outer skins of buildings can define its value, performance and architectural expression. As the interface between interior space and the exterior environment, building façade plays a crucial role to create a more comfortable interior by collectively reducing overheating, air conditioning costs and excessive heat loss. Its performance in that role affects occupant comfort and productivity, energy use and running costs. A wide variety of façade systems may be used in monuments and buildings, which include brickwork and stonework (masonry), curtain walling, exposed structural systems, glass and steel façade systems.



(a) Red brick mill (b) Facade of Ad Deir

(c) The Ave Maria Oratory (d) The Crystal

Figure 2.1: Various types of building from ancient to modern facades

A compilation of façade systems is depicted in Figure 2.1: (a) Red brick mill was built in 1904 by a German, Gerhardt and ruined during the World War 2, as a war monument in a center of Volgograd, former Stalingrad; (b) Facade of Ad Deir, the ancient rock-cut monastery was built in 2nd century C.E. in Petra, Jordan; (c) The Ave Maria Oratory was built in 2007 in Ave Maria, Florida as the central feature of the university, features a distinctive steel structure, which is largely exposed both internally and externally; (d) The Crystal, new headquarters of the Nykredit bank glass façades supported by a steel skeleton completed in 2011 in Copenhagen, Denmark.

Masonry facades can be formed by supporting brick or natural "hand-set" stone panels from storey-height precast concrete panels. An exposed structure facade indicates that a building's structural framework is not covered. Curtain walling is an outer covering of a building made of metallic lightweight cladding or glazed cladding systems that are directly supported by a structural frame. One of the major trends of contemporary architecture is to link interior space to the exterior with minimum compromise using glass facades. Structural glazing and the use of glass as a structural element are making their way into mainstream building projects. The most common structural glass applications are supporting floors and roofs, glass frames and fins for glazed facades. Structural glass facade technology has gradually emerged in recent decades, driven largely by the pursuit of transparency in the building façade and the integration of glass components into the structural system. In structural glass facades (SGFs), load acting on the glass is transferred to the structural system via glazing system and finally to the beams or columns of building structures.

2.2 Glass

According to the Getty's Art and Architecture Thesaurus, glass is an amorphous, inorganic substance made by fusing silica (silicon dioxide) with a basic oxide; generally transparent but often translucent or opaque. From ancient times, man has been making use of glass. The very first glass known to stone age people which were used before they learned how to make glass, was naturally occurring glass, especially obsidian (the black volcanic glass). An ancient Roman historian, Pliny attributed the origin of glassmaking to Phoenician merchants in the region of Syria around 5000 B.C. However, archaeological evidence suggests that the discovery of the first man-made glass took place in Eastern Mesopotamia and Egypt around 3500 B.C. and the first glass vessels were made about 1500 B.C. in Egypt and Mesopotamia. Around 1st century B.C., a breakthrough in glass making was discovered, known as glassblowing, the practice of shaping a mass of glass that has been softened by heat by blowing air into it through a tube.

In 1959, Sir Alastair Pilkington developed the float glass process that revolutionized the glass industry and became the universal procedure for the manufacture of high-quality flat glass. Float glass combines the best qualities of both polished plate and sheet glass and is virtually distortion-free. Pilkington's invention thus set out to achieve a uniform thickness and bright fire-finished surfaces as well as eliminate the need for grinding and polishing process (Nascimento, 2014). Nowadays, advance in glazing technology and tendency using transparent material in modern architecture, leads to the idea of utilizing glass more innovatively to provide unlimited design possibilities. Glass has its own load-bearing qualities; therefore, it can be used not only as a part of the building envelope such as filling materials of windows but also as material for load-bearing elements (Veer, 2008).

The term "glass structures" refer to the glass elements that transfer loads other than those imposed directly on to the element. Glass can be used structurally to create roofs, cantilevered balustrades, portal frame, floors, stairs and bridges and to create architectural structures with transparency and lightness (Ledbetter et al, 2006).

2.2.1 Fully Tempered Glass (Toughened Glass)

In general, tempering or thermal treatment is a process where the glass is heated at high temperature to make it more resistant to breakage and create a suitable residual stress field. The tensile surface stress of the tempered glass should be smaller than the residual compressive stress to prevent crack growth or flaw opening as indicated in Figure 2.2.

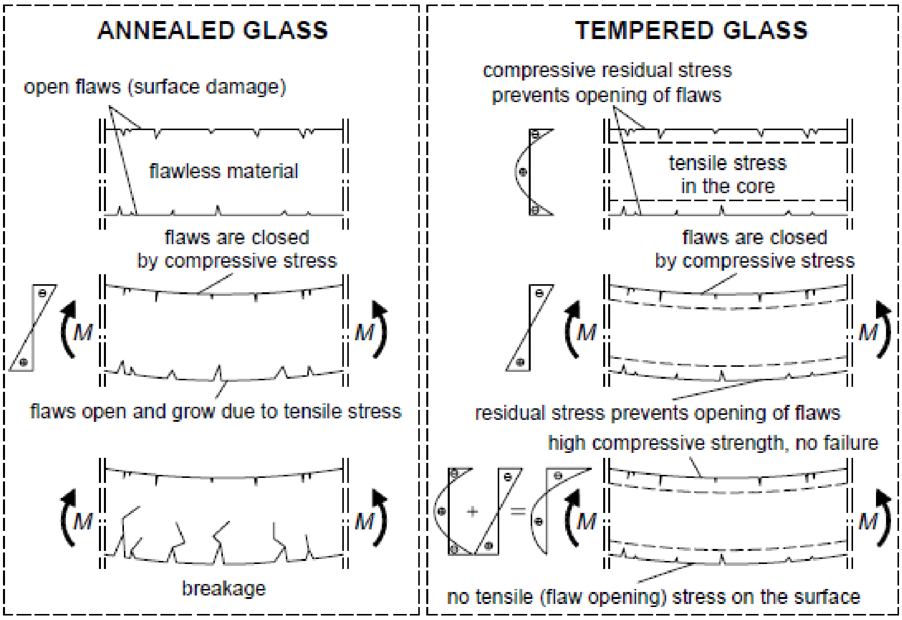


Figure 2.2: The principle of glass tempering (Haldimann et al., 2007)

There are two ways of making tempered glass, either thermally or chemically (Pariafsai, 2016). Chemical tempering causes the shallow depth of pre-compression where glass is more susceptible to surface defects while glass has higher resistance to thermal shock with thermal tempering. Thermally tempered (toughened) glass is produced by complete tempering while the product of partial tempering is called heat strengthened (partly toughened) glass (Pariafsai, 2016). The tempered glass will shatter into very small pieces as a high amount of energy is stored before breakage, both by the prestress and by the higher failure stress (Bos et al., 2005). Although the toughened glass has the highest structural capacity of all glass types, it has poor post-failure performance as it breaks into tiny fragments (Haldimann et al., 2007) due to spontaneous fracture phenomenon (Pariafsai, 2016).

Tempered glass is also made from annealed glass which involved some modifications to the float glass process. Prior to toughening, the float glass which has been cut into the desired shape is washed thoroughly to remove dirt and debris. The float glass is heated to approximately 620 – 675 °C in a furnace and then quenched (cooled rapidly) by jets of cold air during the thermal tempering process as shown in Figure 2.3. The surface of the glass will be solidified first following its interior as the effect of cooling which results in tensile stresses on the surface and compressive stresses in the interior. When the glass interior has cooled down, the cooling leads to the characteristic residual stress field with the surfaces being in compression and the interior in tension.

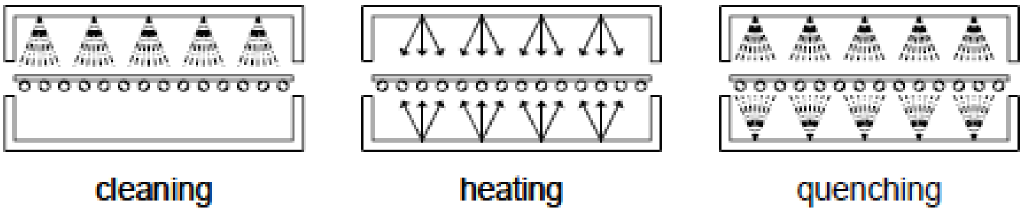


Figure 2.3: Tempering process (Haldimann et al., 2007)

2.2.2 Laminated Glass

Laminated glass consists of two or more glass panes bonded together by a transparent interlayer commonly polyvinyl butyral (PVB) invented by the French chemist Eduard Benedictus in 1903 as demonstrated in Figure 2.4 (Mocibob, 2008). Lamination is a process when the interlayer is sandwiched between the glass sheets, heated at 140° and pressed up to 14 bars to expel air inclusions and form the bond. The structural behaviour of glass can be modified both before and after breakage through lamination process (Bon, 2003).

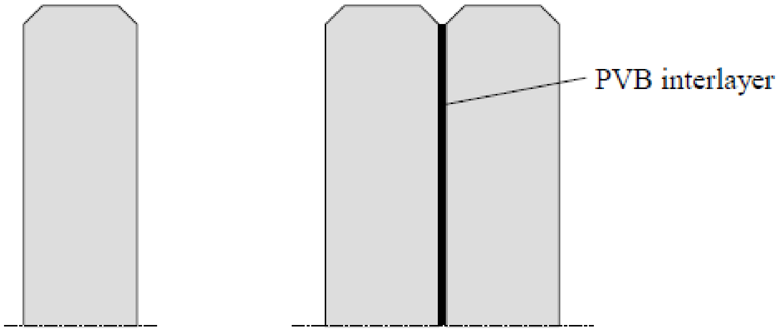


Figure 2.4: Glass products: monolithic glass (left) and laminated glass (right) (Mocibob, 2008)

Lamination of a transparent plastic film between two or more flat glass panes can improve the post-breakage behaviour as the interlayer holds the fragments together, prevents the glass from breaking up into large sharp pieces and continues to provide residual resistance after breakage (Mocibob, 2008). Structural capacity and post-breakage behaviour of laminated glass (can be made from annealed, toughened or heat strengthened) depends on the glass fragmentation and interlayer respectively (Haldimann et al., 2007) as shown in Figure 2.5.

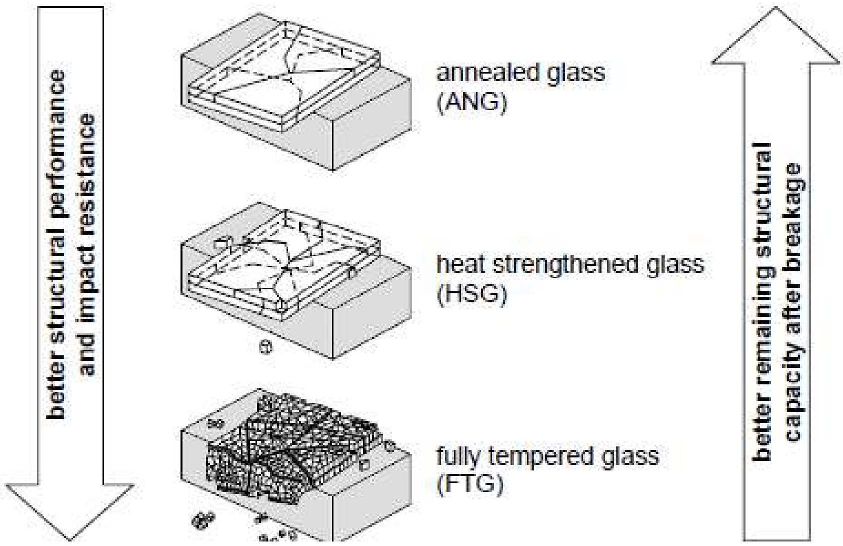
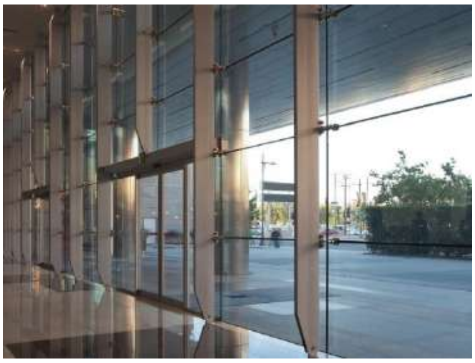


Figure 2.5: Post breakage behaviour of laminated glass made of different glass types (Haldimann et al., 2007)

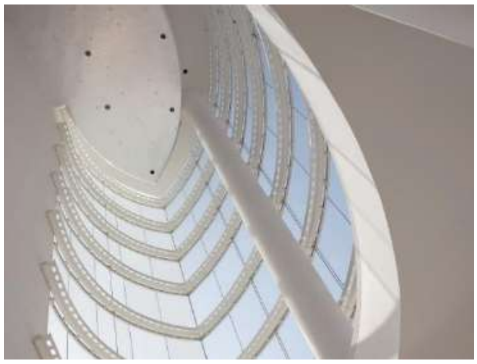
2.3 Structural Support Systems

Modern facade technology has gradually emerged in recent decades, driven by the demand for more responsive facades which lead to the replacement of conventional glazing. New glazing systems with the most popular point-fixed systems are also a part of this new generation of high-performance facade technology.

An interesting diversity of structural support structure types has evolved in these long-span façade applications, with each type possessing varying attributes to develop an optimum solution to the façade design (Patterson, 2008). The supporting structure can be in various configurations such as mullion and transom, truss system, mast truss (guyed strut), glass fin, grid shell, and cable-supported structures as depicted in Figure 2.6. All these systems follow the main goals which are to maximize transparency and provide structural support.



(a) L.A. Live Tower Residences



(b) Orange County Performing Arts Center

(c) Walter E. Washington Convention Center

(d) 32 St Georges Terrace, Perth

Figure 2.6: (a) Vertical mullions at the L.A. Live Tower Residences; (b) Horizontal mullions at the Orange County Performing Arts Center; (c) Vertical trusses at Walter E. Washington Convention Center and (d) Laminated glass fins at 32 St Georges Terrace, Perth

2.4 Glazing Systems

The glass component of building's façade or internal surfaces is referred to as glazing. In structural glass facade, engineers first must put it through a process called “glazing system” to secure the glass to the structural support systems by relying on steel support structures and provide weather sealant for the façade (Yussof, 2015). In this regard, rapid evolution in glazing technology and development has led to a wider range of design options. There are two types of modern glazing systems that can be used with structural glass facades, namely, framed and frameless glazing systems.

2.4.1 Framed Glazing System

Framed glazing system comprises of four main components as demonstrated in Figure 2.7. Generally, steel framing members represent load-bearing structure. Glass is integrated with other cladding systems, inserted between two or more members and is then continuously supported either along two or four sides (Bon, 2003).

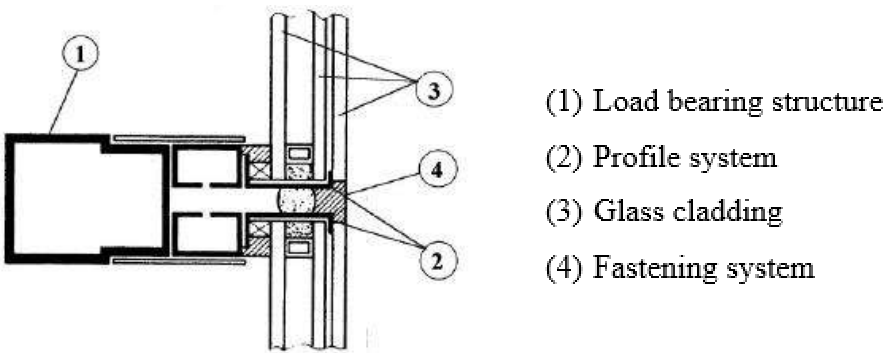


Figure 2.7: Framed glazing system (Kallioniemi, 1999)

Framed glazing systems such as curtain walling have rapidly developed until metal frame assembly glazed with architectural glass become one of the popular configurations. These systems typically consist of vertical and horizontal structural aluminium framing members, known as mullions and transoms respectively (Taywade and Shejwal, 2015), attached to the supporting structure of the building and in-filled with the cladding panels (Khoraskani, 2015). The curtain wall is the outer envelope of a building made up of lightweight material and categorized as a non-bearing wall as it does not carry the structural load (Khoraskani, 2015). There are three types of curtain wall; stick system, unitized (unit panel) system and semi unitized (unit mullion) system (Taywade and Shejwal, 2015).

a) Stick System

In this system, aluminium frame components are prepared and machined in the factory and the installation works are performed on site (Khoraskani, 2015). The glass or other cladding panels are then connected to these framing members.

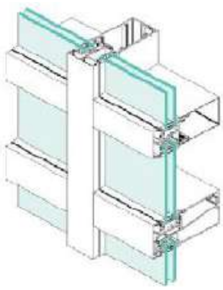


Figure 2.8: Stick system (Glazette, 2013)

b) Unitized System (Unit Panel System)

Unitized is a term used to describe a system in which large-assembled frames, with interlocking mullions and transoms, are built up under controlled conditions in the factory. The entire units are shipped to the site for erection.

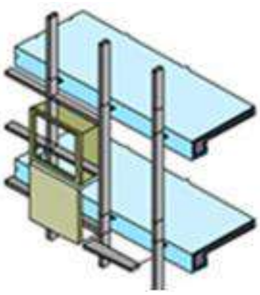


Figure 2.9: Unitized system (Allure System, 2016)

c) **Semi Unitized System (Unit Mullion System)**

Curtain wall components are fabricated at the factory, delivered to the site for the framework and assembled them into the unitized panels. Glass is structurally glazed by weather silicone to aluminium subframe and the subframe with the glass is then bolted to the main frame and installed on the grid work.

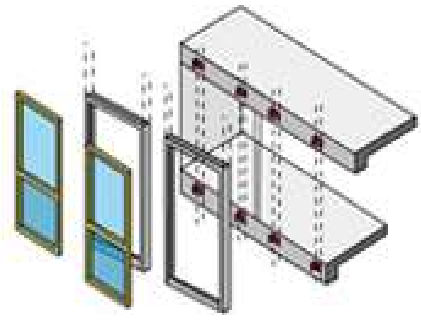


Figure 2.10: Semi unitized system (Glazette, 2013)

2.4.2 Frameless Glazing System (Point-Fixed System)

A typical arrangement of frameless glazing system which consists of four basic components is illustrated in Figure 2.11. This glazing system is often bolted to steel support structure to provide point support to the glazing panel instead of the continuous edge support provided by conventional frames (Ryan et al., 1997).

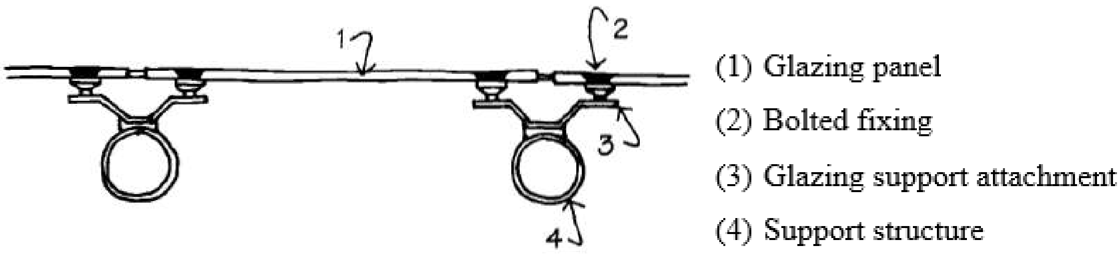


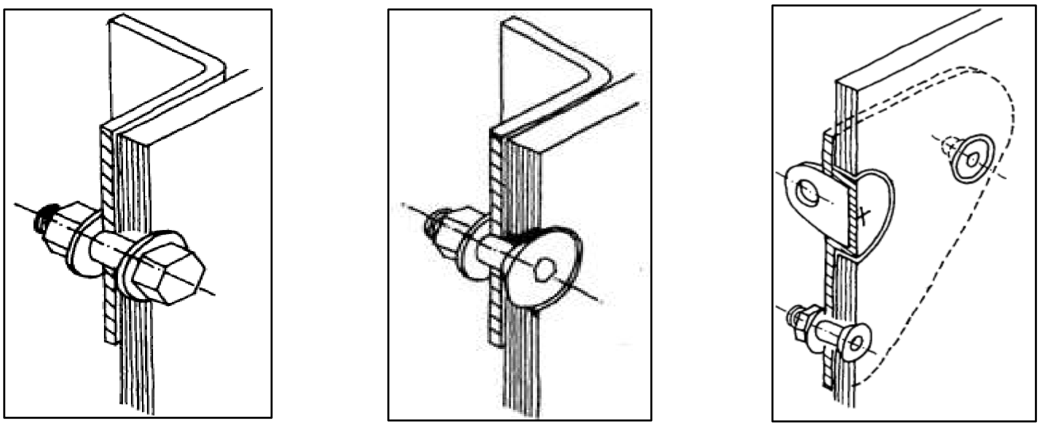
Figure 2.11: Frameless glazing system (Ryan et al., 1997)

i. Glazing panel

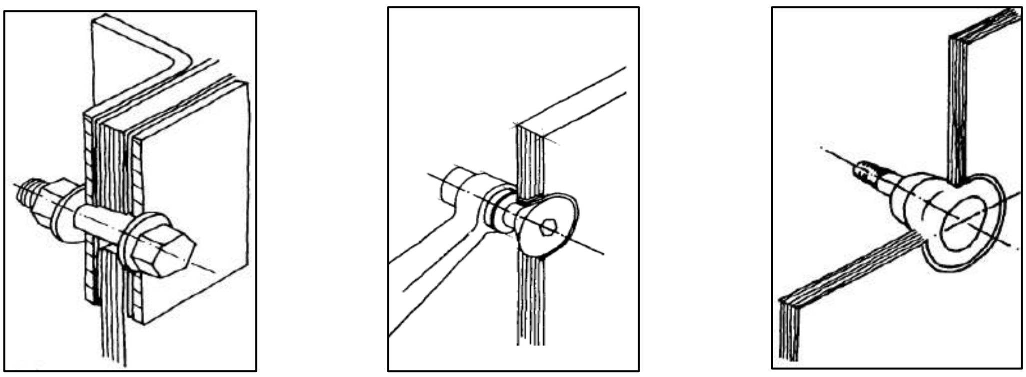
Glazing panel is transparent or translucent materials, usually glass is used as infill within wall or roofing system (Ryan et al., 1997). The exterior of a building is often covered with a different composition of glazing which may consist of either monolithic, laminated or double-glazed unit (Dowdle and Cole, 1999). Selection of glass cladding should consider the maximum amount light is able to go through the glazing and can also eliminate the glare that would produce undesirable contrast levels. Stresses at the hole and deflection of the glass will influence the selection of glass thickness (Vyzantiadou and Avdelas, 2004; Dowdle and Cole, 1999).

ii. Bolted Fixing

Bolted fixing attaches the glazing panels to glazing support attachments (Ryan et al., 1997) and transfers the glass self-weight and lateral loads to the intermediate support (Vyzantiadou and Avdelas, 2004). Those bolted connections are commonly located toward the corners of glazing panels or additionally at intermediate points on long edges as the glazing support attachments (Ryan et al., 1997). Bolted glass connections comprise either a bolt through the glass that bears on the glass (load transfer by bearing) or friction plates that are clamped on to the glass by bolts that do not contact the glass (load transfer by friction) (Ledbetter et al., 2006) as shown in Figure 2.12.



(a) Standard bolt (b) Simple countersunk bolt (c) Stud assembly

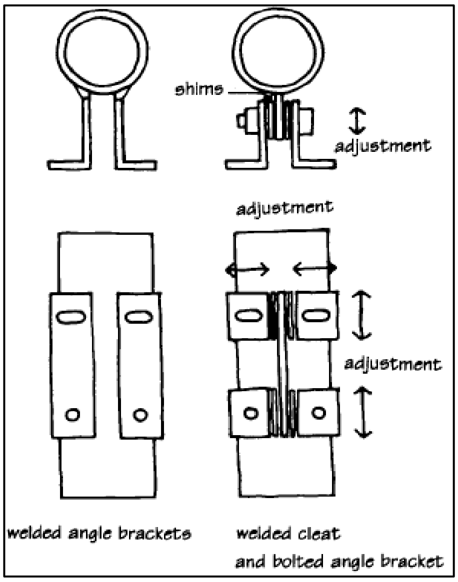


(d) Patch plate fixing (e) Enhanced countersunk fixing (f) Articulated bolt fixing

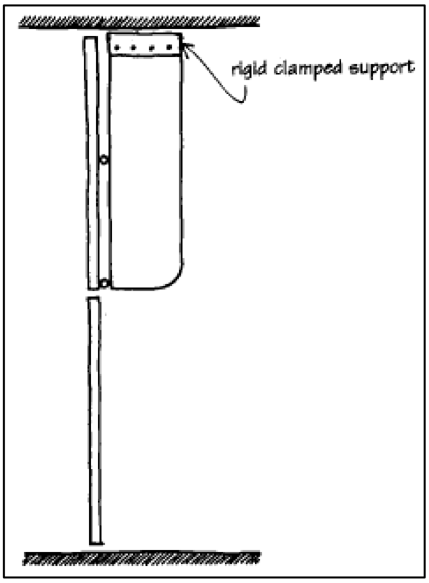
Figure 2.12: (a) Standard bolt; (b) Simple countersunk bolt; (c) Stud assembly; (d) Patch plate fixing; (e) Enhanced countersunk fixing and (f) Articulated bolt fixing (Ryan et al., 1997)

iii. Glazing Support Attachment (Intermediate Support Fixing)

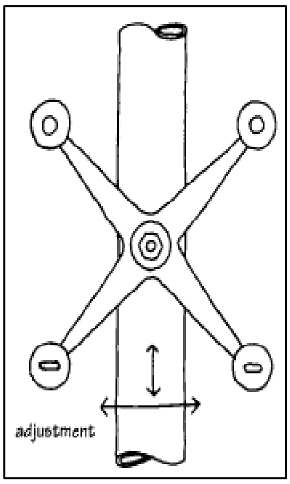
An interface between the glazing panels and the support structure is referred as glazing support attachment. These attachments provide a point of attachment for mechanical fixing and transfer loads to the main support structure (Dowdle and Cole, 1999). The intermediate support fixings are varied, with many designed specifically for attachment system and these range from simple fin plates to more complex 'pin and spider brackets' (machined or cast) as shown in Figure 2.13.



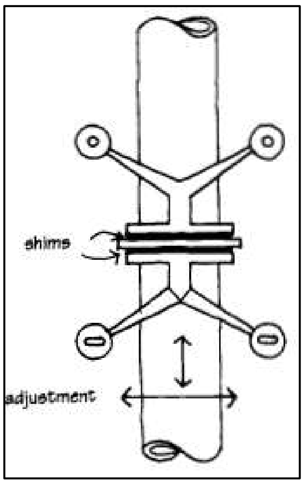
(a) Angle brackets



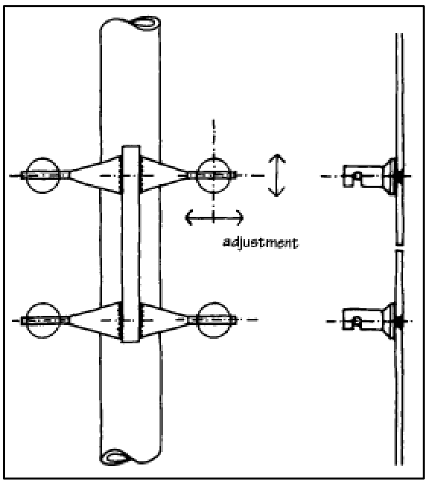
(b) Clamped cantilever glass fin



(c) Single bracket spider



(d) Paired bracket spiders



(e) Paired pins

Figure 2.13: (a) Angle brackets; (b) Clamped cantilever glass fin; (c) Single bracket spider; (d) Paired bracket spiders and (e) Paired pins (Ryan et al., 1997)

iv. Glass Support Attachment

The support structures such as steel beams, column or trusses transfer loads including self-weight, wind and other imposed loads from the glazing support attachments to the building structure or to foundations. There are two main types of point-fixed structural glazing systems: point-fixed bolted system (also known as spider system or bolted assembly) and point-fixed clamped system (also known as pinch-plate system or patched assembly) (Yussof, 2015 and Khoraskani, 2015).

a) Point-Fixed Bolted System (Spider System or Bolted Assembly)

Point-fixed bolted system involves the integration of the bolted fixings and the glazing support attachments which are used to connect the glass panes to their support structure completely through mechanical fastening (Khoraskani, 2015). The connection bracket is fastened to the glass by special bolts through the holes provided at the corners of glass panels as shown in Figure 2.14. The bolts are also used to transfer the entire weight of the glazing panels to the connection bracket. Therefore, connection bolts should be flexible especially with respect to rotation to prevent stressing the glass after the installation (Khoraskani, 2015).

Figure 2.14: Point-fixed bolted glass system using a spider fitting and perforated glass (ArchitectureWeek, 2011)

b) Point-Fixed Clamped System (Pinch-Plate System or Patch Assembly)

Patched assembly systems mainly rely on friction for the fixture of the glazing panels to the attachment brackets (Khoraskani, 2015). The corners of the glass panels are held in place by metal plates, usually in the form of rectangular patch plates and held together by applying a pressure. The patch plates are applied at both sides of the glazing panel and clamped together to generate a normal force and a corresponding frictional load capacity in the plane of the glass (Ledbetter et al., 2006). A suitable interface such as pure aluminium or fiber-reinforced plastics can be placed between the glass and the plates to provide the required coefficient of friction.

Figure 2.15: Glass panes are attached using clamp fittings at panel corners in point-fixed clamped system connected to cable structure (ArchitectureWeek, 2011)

2.5 Glazing Method

Instead of using mechanical elements such as pressure plates and gaskets, a weather seal such as silicone sealant can be used alternatively to fill in the space between the glass panes and the glazing system. Non-structural glazing methods such as wet glazing, dry glazing and a pressure-glazed system can only provide sealant against air and water infiltration as stated in Figure 2.16.

The term "structural" should only be applied to the sealants which become an integral part of the structural glazing (Vallabhant et al., 1997) as they can transfer stresses resulting from the dynamic wind load and self-weight of the glass to the perimeter structural support (Ledbetter et al., 2006). Thus, those sealants are identified as structural sealants (Vallabhant et al., 1997) and the term "structural glazing" is commonly used to describe structural sealant glazing (SSG) (Ledbetter et al., 2006).

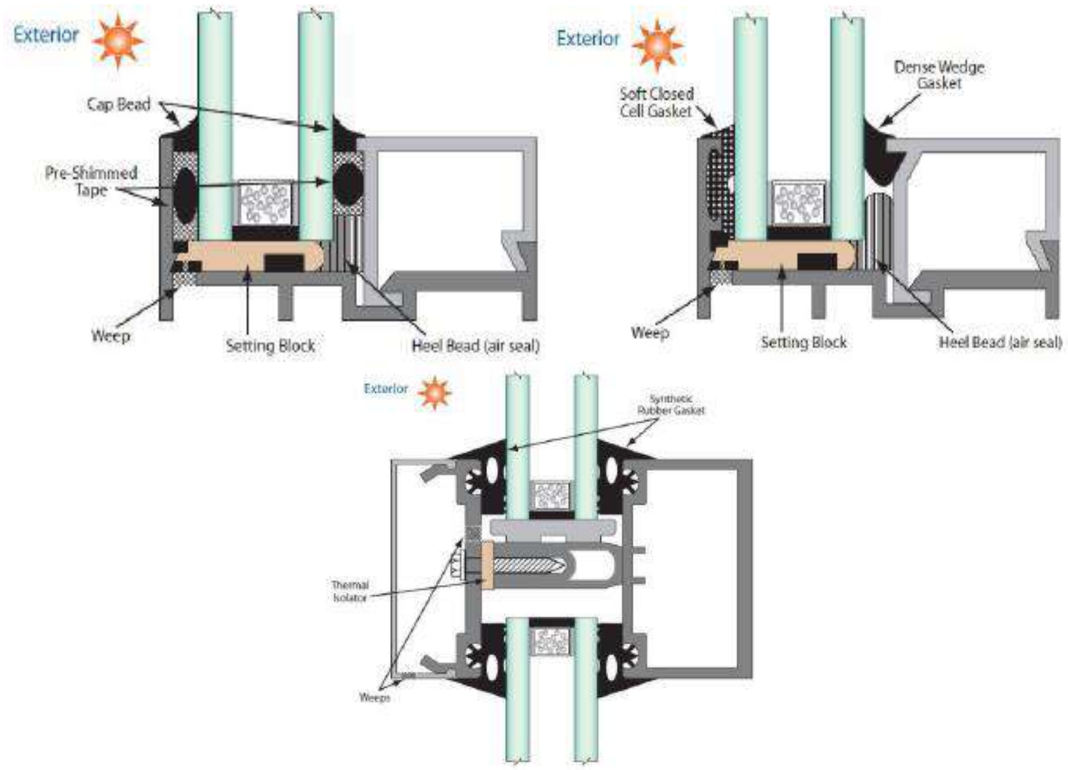


Figure 2.16: Wet glazing (top left), dry glazing (top right) and pressure-glazed system (bottom) (Yussof, 2015)

2.5.1 Structural Sealant Glazing (SSG)

Structural glazing is a system of bonding glass to a building's structural framing members utilizing a high strength silicone sealant to eliminate the need for conventional aluminium frames or mullions. SSG systems are specifically designed into two and four-sided bearing as shown in Figure 2.17. There are four major conditions which include wind load, dead load, differential temperature expansion of the glazing unit and climatic loads that must be emphasized in designing the structural glazing (Kallioniemi, 1999).

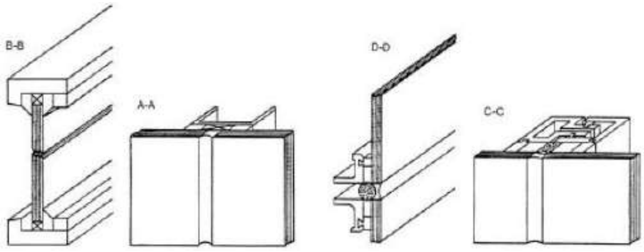


Figure 2.17: Two-sided (left) and four-sided (right) of SSG (Kallioniemi, 1999)

Butt-joined sealant has become a popular weather seal used in frameless and SSG as a method of finishing building exteriors, especially multi-storey buildings (Vallabhant et al., 1997). SSG is suitable for smooth, transparent external glazed surfaces is commonly referred to as crystal cladding where the exterior surface is required to be free from protrusions and top over framing (Khoraskani, 2015) as represented in Figure 2.18.

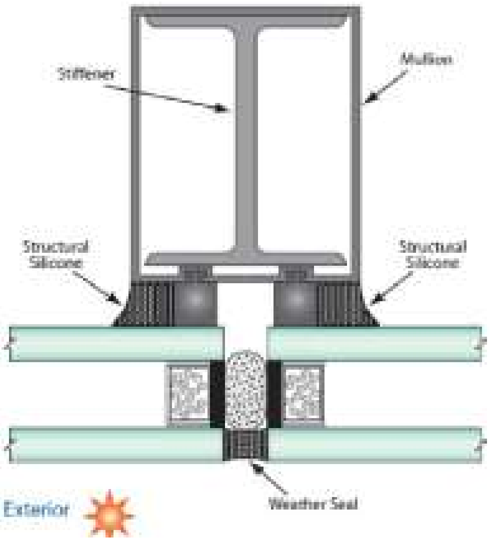


Figure 2.18: SSG (Yussof, 2015)

2.6 Performance of Glass

Glass shows an almost perfectly elastic and isotropic behaviour because of its non-crystalline molecular structure. The tensile strength of glass depends very much on mechanical flaws on the surface, therefore glass tends to exhibit brittle fracture. For safety purpose, brittleness property has to be considered in structural glass facades because most glass failure cases do not originate only from points of maximum tensile stresses (Kallioniemi, 1999). Local stress concentrations in the glass cannot be reduced through stress redistribution as the glass does not yield plastically (Haldimann et al., 2007). Unlike steel and aluminium where plastic mechanism can be formed, breakage occurs immediately without warning when the glass is stressed beyond its strength limit.

There are two typical effects on the behaviour of glass as a building material. Firstly, size of glass element, action history (intensity and duration), residual stress, surface and environmental conditions (dry, wet or humid) influence the tensile strength of glass. Secondly, the larger the stressed surface area and the more uniformly the stresses are distributed results in a higher probability of failure. Factors influence strength of glass in the region of bolt hole are complex stress state, inherent strength of glass and magnitude of residual thermal stresses. Inherent glass strength depends on the surface condition, loading history and environmental conditions (Haldimann et al., 2007).