University Of Southern Queensland

Faculty of Engineering and Surveying

Design of Structural Glass Fitting for Seismic Condition

A dissertation submitted by

Heng Hern

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Abstract

The use of point bolted system to hold the glass panes of a building is becoming very popular nowadays. Many Architects are beginning to substitute the curtainwall or framed glass wall with the frameless, dot point types. It makes use of stainless steel glass fittings to hold these glass panes and in elevation, it provides a clear, transparent effect.

Most current glass fittings have all fixed arms, which are used for transferring loads from facial glass panes to the structural members. They are commonly used in non-seismic zones countries and are not designed to use in seismic conditions.

With the new system, which provides more flexibility, the arms on the fittings are made to articulate which enable the glass to move freely during an earthquake. In order to do that, we are required to have a clear understanding of the seismic design process and to be able to perform steps to establish the movement response parameters.

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Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertations are entirely my own effort, 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.

Heng Hern

Student Number: D10354144

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Acknowledgement

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HENG HERN

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Chapter 1

Introduction

A growing number of architects are substituting the design of framed curtain walls with frameless glass walls. With proper planning, these unconventional glass walls can provide energy savings by allowing natural light to enter the building. In addition, they enhance performance, safety, and aesthetic appeal.

The transparency of the glass depends on the relative amount of light on either side of its surface. If there is more light on the viewer side, then it becomes reflective. On the other hand, it will be transparent. A glass skin determines the levels of light and heat or leaving a building. Some ways of reducing the heat gains/losses include changing the composition of the base glass in the case of single glazing, or through the addition of various interlayer to achieve specific properties in the case of laminated glass. Effective solar control can also be achieved by the use of reflective coatings to further reduce the level of energy transmission. For examples, the addition of metal oxides to the base glass leads to a stronger tint, which produces a higher ratio of absorption. As a result, there will be a reduction in the solar energy entering the building on a very hot day. The use of low emissivity, or low –E coatings can also reduce the infrared radiation up to 20%, without bringing the light transmission down tremendously.

The technique of fixing glass and exploiting its structural capacity allows structural elements such as mullions or glazing bars to be eliminated from the glass plane. This has a particular potential in architectural expression in terms of transparency, By removing these mullions and aluminium profiles from the pure planar nature of the glass surface, gives it a relief standing out from the transparent planes.

Background

One method of providing a frameless glazing façade is to fix together a matrix of toughened glass lites hung from the building structure. Such a system, commonly referred to as a suspended glass assembly, was first designed in the 1960s. It allowed designers to glaze large openings in buildings as high as 40m without using metal frames or mullions to create light and space with a minimum of visual barriers.

Many systems are now available for the use of glass in facades, all aimed at achieving maximum transparency by reducing the non-support structure. In close collaboration with the glass industry, many architects have worked on the possibilities of glass for use in buildings. The two most common systems include the Patch Plate Glazing and the Dot Point Glazing.

The patch plate suspended glazing system is the earliest system. It comprises a series of specially processed and toughened glass lites bolted together at their corners by small metal patch fittings. Pane-to-pane joints are sealed with a silicone building sealant, and toughened glass stabilizers or steel plates are used at each vertical joint to provide lateral stiffness against wind loading. The assembly is suspended from the building structure by hangers bolted to its top edge and is sealed to the building in peripheral channels. The concept of the design ensures that the façade is at all times, "floating" in the peripheral channeling, and the problems which might arise due to differential movement between components are eliminated. Sealing is carried out at all joints in the façade using either the structural or weather- proof sealant depending on the load transfer intent of the system. The principle behind the design of the fittings for a suspended glazing assembly is that all in-plane forces transferred between components are resisted by friction developed at the metal/gasket/glass interfaces arising from the tension of the fixing bolts. The friction grip is of particular importance in the design of the splice joints and root support of the stabilizers where the bearing strength of the holes are unlikely to resist the turning moments generated in the stabilizers which is caused due to the wind forces. If required, the coefficient of friction at the metal/gasket/glass interfaces can be enhanced by applying a suitable adhesive. The façade lites resist lateral wind forces through the small metal patch plates supporting the four corners of adjacent lites off the stabilizers, These metal patch plates clamp the glass at the corners of each pane, developing significant stress concentrations at the edges of the plate and around the bolt holes. To safely design this system, it is essential to have detailed knowledge of the stresses generated and also the knowledge of the strength of toughened glass.

One of the features of a patch plate suspended glazing assembly was that it could not be used in conjunction with sealed insulating glass units (IGU) or any non vertical applications, such as the sloped glazing. The Dot Point Glazing System (DPS), sometimes called the “Spider” glazing can be used for both cases. It has been increasingly popular to support glass using bolted fixings directly connected to the glass. These fixings allow improved transparency and offer architectural opportunities in detailing the bolted connections and fittings. It is capable of fixing either the monolithic (single lite) or insulating toughened glass to any structure. In some cases, glass mullions are used to form part of the substructure to which the glass is attached. This system is used for vertical or sloped glazing and can be incorporated as a complete cladding system. The fittings are designed to support the weight of the glass by direct bearing of the bolt through the bushing on the hole in the glass. The fitting is also designed to give minimal clamping by attaching the fixing bolt which is flexible and allow rotation of the glass. Recent designs on the fixing bolts also have provision for articulation or ball-type joints. The overall effect is to significantly reduce the stresses developed in the glass in the region of the planar fitting compared to those developed around the patch plates. It allows the panes of glass to move in relation to their supporting structure while maintaining a smooth outer surface appearance. When large piece of glass bend under wind loads, a high load concentration will occur in the area of the hole if the fixing bolt is firmly fixed to the supporting structure. In brief, the above underlines the following design issues:

- A supporting system at point locations causes high load concentrations;
- A hole in the glass is very sensitive, especially when it is countersunk;
- Enlarging the hole can reduce the load in the bearing surface;
- Articulated assemblies allow the differential movements between the glass and the structure to be absorbed.

Because frictional forces and hence the clamping forces are not important in the design of the planar fixing, its design is suitable for use in the insulating glass version. In this, the outer lite provides the main load bearing capability. Careful research into the stresses, especially around the hole is necessary in the design of this type of system. Because the glass lites are individually mounted to the structure, there is no restriction on the height of the buildings which can be glazed.

Most standard typical fittings consist of two or four fixed arms, depending on the location of glass, whether glass is adjacent to the concrete structure or to the glass itself. Considering a typical 4-legged fitting with an M10 bolt at each arm, enlarged holes usually diameter 22mm are normally used at the end of the nodes on both the top two arms. These enlarged holes allow for both horizontal and vertical adjustment during installation. A horizontally elongated hole and a nominal hole, usually 11 X 22mm and diameter 11mm respectively are provided at the bottom two arms. As most glass wall systems are suspended, these arrangements are necessary for proper transfer of loads.

Scope Of The Thesis

However none of the system described above is suitable for use in highly seismic environments. With the increasingly advancement in buildings technology, a solution under this condition is worthwhile to be investigated. For instance, the project I am currently working on: CalPERS Headquarters Expansion Project happens to be located in a seismic region. The project consists of a glass pavilion located in Sacremento, United States, which is in a seismic zone 3 area. The basic architectural objective of this project is to make the public subtly aware of the transparent plane it is supporting. It attempts to remind the viewers of the presence of the plane of glass, while at the same time, maximizing the transparent qualities. From inside, the eyes recognize a series of points and lines (spiders and mullion supports) which define a plane in space; from outside, the glazed plane is materialized in the form of perfectly smooth and uninterrupted reflective skin. The glass pavilion is measuring 16m x 16m x 30 m in height and it uses a tempered laminated tinted glass with low-E coatings to improve the thermal insulation properties of the glass. This will be the first structural glass wall to use a special designed fitting for seismic in the United States. The aim of this project is to design the fitting for the glass panels.

Chapter 2

2 Design Criteria

2.1 Design Specification

The loads specified herein are based on information provided by Lee Herzog of Citadel Consulting. The specification information is based on the design and structural analysis carried out during the pre-contract phase of work. This report applies solely to the steel elements shown on the Entry Pavilion drawings. The design-build contractors, including M/s United Reliance Engineering Pte. Ltd must satisfy ourselves as to the extent and scope of analysis require to prepare complete construction documents for fabrication and installation.

The analysis model on the pavilion tree used in this phase is coordinated geometrically with the cladding envelope geometry. The model is a full tree-dimensional representation of the structure using finite elements. The model has all gravity and wind loads applied directly to it. The seismic response is studied with the dynamic procedure as described above. The permanent attached masses from steel structure and cladding are represented.

2.1.1 Structural Design Method

The Structural Design Method are as follows:-

Structural Glass:	Permissible Stress Design
Structural Steel:	Load and Resistance Factor Design
Aluminium:	Permissible Stress Design
Concrete Anchorage:	Ultimate Strength Design

2.1.2 Materials

2.1.2.1 Glass

Table 2.1.2.1(a) shows the Properties of Glass

Properties	**Young's Modulus**	**Unit Weight**	**Poisson's Ratio**
Glass	72GPA	25.6KN/M3	0.22

Table 2.1.2.1(b) shows the Permissible Bending Stress of various glass

Bending stress	**On Surface**	**On Edge**
Fully Tempered Glass	73.5 MPA	49 MPA
Heat Strengthen Glass	45.9 MPA	37.3 MPA
Annealed Float Glass	19.6 MPA	17.6 MPA

2.1.2.2 Sealant

The Structural sealant shall be DC 795 and will be site applied. The Permissible stress will be as follows:

Table 2.1.2.2 shows Permissible stresses for DC 795

Permissible stress	0.138 MPA	For Wind Load
	0.0069MPA	For gravity Load

2.1.2.3 Structural Steel, Stainless Steel & Aluminium

The Structural Steel is a high-strength low alloy steel, Stainless Steel is of Grade 316L.

Table 2.1.2.3 shows the allowable strength of materials

Material	Young's Modulus	Yield/ULT Strength
Structural Steel (A572)	200 GPA	289MPA / 482MPA
Stainless Steel (BS 5950)	205 GPA	205 MPA / 490 MPA
Aluminium (BS 8118)	70 GPA	130 MPA / 275 MPA

2.1.2.4 Connection Bolt For Structural Steel

Connection bolts for steel mullions, vertical, horizontal and cross bracings, shall be high strength bolts conforming to ASTM A325, Type 1, 'Medium carbon steel' or equivalent.

Erection bolts shall be ordinary bolt conforming to ASTM A307, grade A, 'Carbon Steel Black Bolts'.

2.1.3 Loading

2.1.3.1 Dead Loads (DL)

Unit weights of major construction materials:

Structural Glass 25KN/M3

Structural Steel 77KN/M3

2.1.3.2 Live Loads (LL)

Roof 0.6 KN/M3

Construction 2.5KN

2.1.3.3 Wind Load (WL)

The diagrams shown in Appendix B1-1 & B1-2 describe the different patterns of exterior coefficients used in the analysis of the structure. These patterns make allowance for the partial 'shading' of one side of the Entry Pavilion by the building.

Particular attention shall be paid to wind load patterns that cause out-of-balance conditions and torsion of the structure.

Wind Load for the wall elements and their supporting system shall be based on 1997 Uniform Building Code and as calculated herein:

$$P = Ce.CqQsIw$$

Where:

Basic wind speed = 90 MPH (40.23m/s)	
P = 1.36KPA	Effective Design Wind Pressure
Ce = 1.13	Combined height, exposure and gust factor coeff.
Cq = 1.20	Pressure coefficient for wall element
Qs = 1.00 KPA	Wind stagnation pressure
$= 0.000613 \times (40.23)^2$	
Iw = 1.00	Importance factor of the structure

2.1.3.4 Seismic Load (EQ)

The seismic design process has been performed in steps to establish upper and lower bound force and movement response parameters. The structural system considered herein is lightly damped and due to the presence of prestressed tension members exhibits non linear behavior and tension-stiffening effects. In addition, the response of the structure is sensitive to certain parameters such as the damping and the stiffness of the support points, amongst other factors. The seismic analysis procedures selected therefore must address these issues.

The principal design criteria for the seismic design are:

- The structure will remain elastic during the design seismic event.
- The 'hangers' will stiffen the cantilever 'tree' structure.
- The 'hangers' will not go slack.

Seismic inertia loads for the wall elements shall be based on the 1997 Uniform Building Code and as calculated herein:

The total design lateral seismic force, Fp, shall be determined from the formula:

$$Fp = Ap.Ca.Ip/Rp.\ (1 + 3hx1.00/hr).\ Wp$$

Except that:

Hx = The element or component attachment elevation w.r.t. grade

Hr = The structure roof elevation w.r.t. grade

Ca = 0.36 for Sd at zone 3

Ip = 1.00, Structure importance factor for earthquake load.

Ap = Exterior wall element of structure braced above their C.G

Rp = 3.00, Exterior wall element of structure braced above their C.G

2.1.4 Codes And Standards

International Codes and Standards:

- International Convention Of Building Officials (UBC ,1997)
- American Institute Of Structural Engineer (LRFD 1994)
- American Welding society (AWS)

References

- American Society Of Civil Engineers Manual.
- The Institute Of Structural Engineers, London, 1999
- Structural Use Of Glasses In Buildings
- Standards Australia. Glass In Buildings

Materials Standards

- American Society Of Testing And Materials (ASTM)

Chapter 3

Design Methodology

The approach to the analysis of the entire system is performed in an indirect " Logical Event" manner whereby the lateral drift analysis is generated through the following assumptions:

The main structure drift as provided by the consultant is the general-level displacement of the hoops relative to their original position (i.e. no differential displacement at any point on any one hoop is associated). The hoops maintain their shapes (plan view) even during lateral drift, hence the steel mullions maintain their spaces between one another horizontally. As the hoops at each level shifted laterally, the mullions rotate accordingly. The mullions rotate as an effect of lateral drift in a rigidly non-deflected manner.

The resistance of the ultra-low modulus sealant against the tilting of the mullions is neglected in this case, thereby allowing the glass to rotate freely.

An AutoCAD model consisting of the mullion, fitting and glass is also drawn. After rotating the mullions at 0.8°, each glass is made to rotate on the fixed arm to confirm that the glass are not in contact. (see Appendix B1-3)

3.1 Glass Behavior During Structure Drift

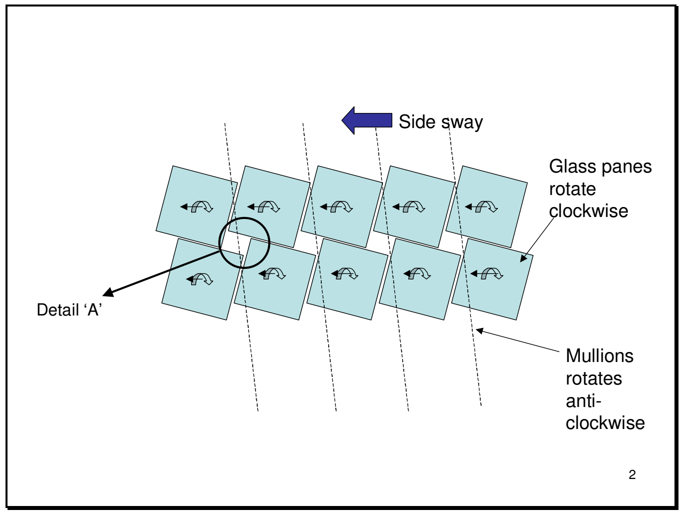


Fig. 3.1(a): Rotation of glass panes under seismic condition

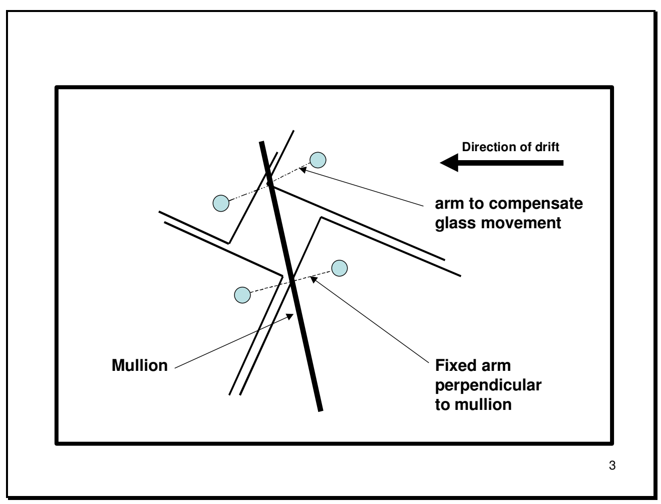


Fig. 3.1(b): Enlarged detail showing the junction of four glass lites

As the direction of drift moves from right to left, the structural hoops slide along each other, with the top hoop drifting to the left and the bottom hoop drifting to the right. This sliding is vice versa when the drift direction is from left to right. This sliding patterns is repeated until the seismic ceases. The steel mullions which are fixed to the hoops at both ends will cause the steel mullions to rotate in the same direction as the hoops. Each glass pane which is suspended from the steel mullions by fixed arms on the fitting is forced to rotate in an opposite direction from the drift since the fixed arm relation to the mullion is also fixed. This is shown in figure 3.1(a) & 3.1(b).

As the glass rotates, pivoting at the top of the glass, the bottom holes on the glass shifted in relation to the mullions. This will require flexible arms to compensate the offset holes on the glass.

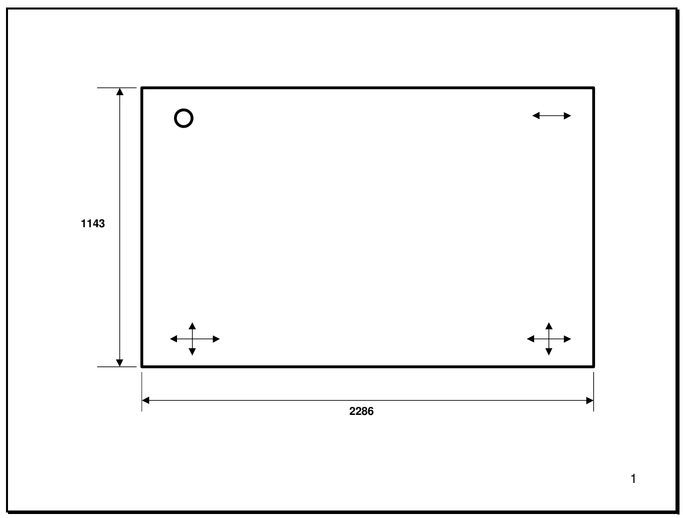


Fig. 3.1(c): Schematic representation of how each piece of glass should be compensated.

3.2 Design of Fitting

3.2.1 Design considerations

Fig. 3.1(c) shows what we should consider in the design so that all the glass panes are allowed to move freely in the event of a seismic occurrence without breaking any of the glass.

Since the glass is suspended via the spider fitting to the mullion, which is then suspended to the primary hoop, the holes provided at the end nodes of the lower arms have to be nominal and horizontally slotted respectively. The horizontal slot allows left/right adjustment so that the error due to mullion installation can be compensated. These lower arms are fixed and are cast in a single mould with the main body frame.

The design of the upper arms has to have provision for both horizontal and vertical adjustments at the end nodes. This is necessary as explained in fig 3.1(a) & (b), so that the glass is able to rotate freely.

At each end node, a ball-joint fitting used to hold the glass onto the fitting is attached. This fitting penetrates the glass holes and allows the large pane of glass to bend under wind loads without high stress concentration. Usually, a countersunk fitting is preferred by architects as it is able to achieve a flush surface. If an articulated assembly is mounted outside the glass pane, bending or twisting loads will be applied to the glass. In the case of Calpers project, the articulated assembly is positioned in the plane of the glass and it ensures no bending or twisting loads can be applied to the glass. The design of the countersunk fitting has to consider the distance between the spider node and the glass surface such that it is able to withstand the cantilever loads. At the same time, it has to be long enough to allow in-out adjustments of glass panels.

The spider body-frame which consists of the body and two fixed arms, has two ϕ11mm holes cast onto the body. Two M10X45L socket head screw holds the entire spider to the mounting block which is pre-welded in the factory. The back surface has horizontal serration cast on it, and these are to mesh those on the mounting block surface.

The mounting block is cast in mild steel (Fig. 3.2.1), as it has to be positioned and welded to the steel mullion. It is specially designed to have a vertical opening to match the thickness of the mullion plate and a smooth concave profile to conceal any exposed nuts and washers. Similar to the spider body frame, the surface where the spider body is in contact, there are horizontal serrations on the mounting block. These serrations when engaged, will provide a well meshed surface and prevent slippage. On this meshed surface, there are two enlarged holes of ϕ25mm. With M10 socket head screw to fix spider to mounting block, a 15mm allowance is allowed for adjustments and this will take care of the left-right and up-down adjustment.

With this arrangement of the spider and mounting block, all three axes, X,Y and Z adjustments on site are provided for.

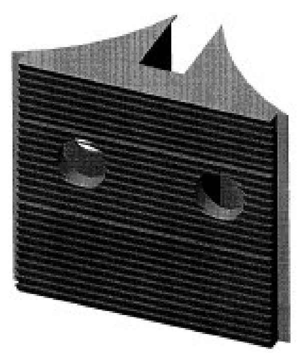


Fig. 3.2.1(a): Front View of cast Stainless steel – Mounting Block

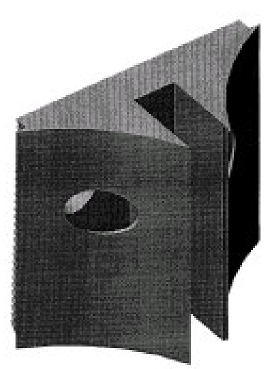


Fig. 3.2.1(b): Back View of cast Stainless steel – Mounting Block

3.2.2 Initial Concepts of Fittings

After the project specification was issued together with the drawings, the design team went into the design phase. The design team consists of the designers and the Engineers. The designers proceeded with the design of the fitting based on the Architect's design intent. Of course, the project architect was not aware of the implication on the glass under seismic condition. The original idea was to have a typical four-legged fixed type. Concurrently, the engineers proceeded with the analysis of the glass using the Finite Element Software. The design started with the detailed study of the behavior of glass under the seismic drift as shown in Fig. 3.1(a), (b) & (c). It was then concluded that the upper arms need to be articulated, whilst the lower arms remain fixed.

Appendix B1-4 shows the initial spider design. It consists of a slim U-shaped body where the steel mullion can be inserted. It has two top extended arms which is mechanically fixed to the body to receive the rod end bearing that provide the articulating effect. At the bottom, there are two fixed arms extended diagonally from the base of the body. The U-shaped body is mechanically fixed to the steel mullion. However, the initial fitting design has few setbacks:

- It is not able to provide for left and right on-site adjustment - The distance between steel mullions installed can be offset by up to 7-8mm. The steel mullion inserted into the U-shaped body has restricted the movement of the fitting horizontally.
- It is not able to provide for up and down on-site adjustment. – The bolts inserted through the steel mullion have restricted the fitting to move vertically. Of course, we can provide vertically slotted holes on the steel mullion, but the weight of the glass, which the fitting is holding on, may cause the spider fitting to slide downwards.
- Aesthetically, the bolts and nuts are exposed. This is not accepted by the architects of records.

3.2.3 Final Design Concept and its Capabilities

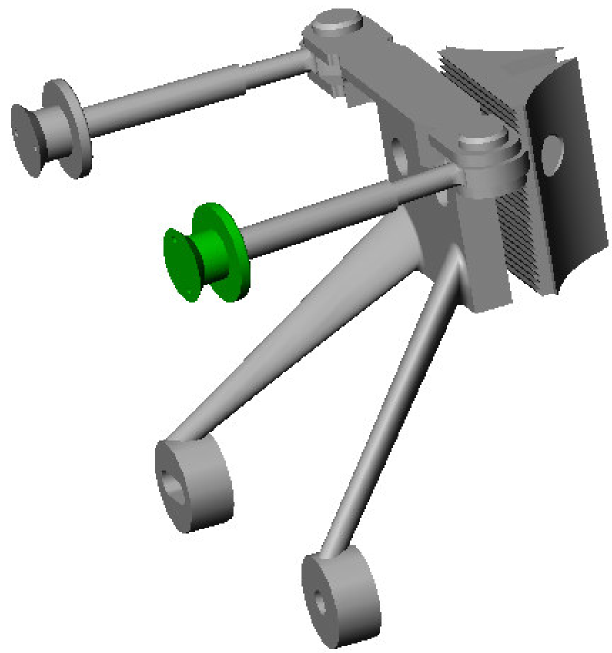


Fig. 3.2.3: Improved Version of Spider Fitting and Mounting Block.

The Articulating Arm is able to have a horizontal free rotation of up to 270 degrees. This is enough to accommodate the approximately 14mm displacement (See Section 3.1 on Glass behavior during structure drift) of the glass due to drift. The Articulating Arm is also designed such that it is able to have vertical translation, as there is a 1mm provision on each side between the Receiver Arm and the Rod End Bearing. The extension rod on this arm allows for in-out adjustment (Z- axes) during installation. The rod ends bearing comprise an eye-shaped head with integral shank forming a housing and a standard radial spherical plain bearing or a spherical plain bearing inner ring and a sliding layer between the bore of the head and the inner ring.

They are available with right or left-hand female or male threads. (See Appendix B1-5A)

The Articulating bolt fixed at the end of the arms is ‘ball joint’ or ‘pinned’ detailed. The bolt, consisting of the stem, ball joint, external collar and support washer are all manufactured in stainless steel of grade 316L. The freedom to articulate will help to relieve the stress on the glass hole edge under loading condition. Alternatively, it provides easy installation of glass when the glass wall is segmented in design.

The Body Frame has two nominal size holes on the flat surface of the body. Two M10X45L socket head screw are used to secure the body to the Mounting Block. The fixed arms on the body are used to suspend the glass, taking the entire dead loads of the glass. One of the holes on the node is a horizontally elongated and the other is a nominal one. These holes arrangement allow for horizontal adjustment during glass installation (X-axes) and at the same time allows the transfer of dead loads to the primary structure via the fittings. A M4 grub screw is also provided at the node with the elongated hole to ‘lock up’ the props after adjustment.

The Mounting Block has horizontal ‘serrations’ on the flat surface of the body. It has also two enlarged holes on the flat surface. These enlarged holes allow a left-right (X-axes) and up-down (Y-axes) site adjustments. As each piece of glass weighs approximately 127kg, the serrated body of the Mounting Block prevents slippage from occurring.

The design of the fitting has not only considered the construction tolerance needed but has other factors to look at as well, e.g. Aesthetics, casting limitations, materials, performance, just to list some. (See Appendix B1-5 for 3D rendering of fitting)

3.3 Water-tightness of the glass panels

The seal between the glass panels are made of silicon. This material is used either as a mastic or as extrusions glued together with mastic. The mastic is used on the small joints between glass sheets in a glass panel, and the extrusions are used on the larger joints between panels. Silicone adheres perfectly with glass when applied according to the following precautions: the glass must be absolutely clean and dry; the area of the joint must not be too wide- this could prevent its total polymerization. Under these conditions, silicone has a remarkable adhesive power, and this can be confirmed by conducting test. The joints expands up to four times their original size, and in case of failure, they are cohesive and not adhesive, which means that the failure will occur in the joints itself and not on the glued surface.

The joint must satisfy three requirements: firstly, it must allow the panels to move in relations to one another; it must not protrude from the glass external skin; and thirdly, it must be watertight.

3.4 Safety in Accidental Breakage Cases

The possibility of the fracture of the glass must be taken into account. Dutton & Rice (1990) theorized that the breakage of a glass sheet would cause immediate changes in the load path of the glass suspension system. Should the upper sheet in a row break, the remaining sheets will no longer be supported; they will transfer their loads to the adjacent sheets of glass through the horizontal casting of the four-hole connection and by producing shear stresses in the silicone joints. The loads applied at the suspension points of the other rows will also be increased. Note that a sudden change in the load path may cause a violent shock at the suspension points.

An innovative design must give confidence to the designers' team and all those who are involved in the project – the client, the contractors, the checking authority – as well as to the general public. Before the implementation phase, a full-scale prototype has to be built and test under resistance to wind, rain and seismic.

Chapter 4

4.1 Fitting and Mullion Construction

4.1.1 Pre-Assembled Fitting (Fig. 4.1.1)

The Spider fittings shall be pre-assembled in the factory prior to the delivery to the job site. The Fitting consists of the following components:

- Body Frame
- Receiver Arms
- Articulating Arms
- Fixed Arms
- Articulated Props (Ball Joints)
- Rod End Bearing
- Dowel Pins
- Mounting Block

The material for the above components with the exception of the Mounting Block is stainless steel of grade 316. The Body Frame and the Receiver Arms are cast using the Loss Wax Investment Casting process to achieve a more accurate tolerance.

The Receiver arm is mounted to the Body Frame mechanically by means of 2 nos. of M8X25L countersunk bolts. The articulating arm or the extension rod is a machined part with both ends threaded, one internally thread and the other externally (male and female). On the male end, the rod end bearing is attached to it, which in turn is secured to the receiver arm by means of a dowel pin and M4X12L countersunk head screw. The screw is smeared with 'Lock-Tite' adhesive before screwing into the dowel pin to prevent loosening due to vibration. On the female end, the articulated prop is attached and these props are used to hold the glass in place.

The two fixed arms are part of the body frame, which are cast and similar to the articulated arms; articulated props are fixed at the ends to hold the glass in place.

The articulated bolt consists of a head, which rotates freely on its stem. The stem ends in a ball on which the head is added using the standard spherical bearing techniques. The head is then machined to the required specifications: countersunk flange, thread, keyholes, etc. A threaded washer is screwed onto the head and holds it against the glass. The washer is tightened to a precise torque so as to avoid any unknown or unpredictable stress.

Steel must never come into direct contact with glass as it has too hard a bearing surface. For this reason, a thermoplastic spacer is commonly used between the steel bolt and the hole in the glass. The slightly ductile nature of this liner ensures that the entire bearing surface of the hole is put to work, not just the high points. Sometimes, pure aluminum liner is used instead, as thermoplastic has a tendency to creep, which eventually will allow the steel to contact with glass.

The Mounting Block is a separate piece and is also cast using the Loss Wax Investment Casting. It is cast in mild steel, mainly because it has to be welded to the structural steel mullion at the fabrication shop before the paint works.

The entire 'spider' assembly is then fixed to the mounting Block with 2 nos. of M10X45L socket head screw.

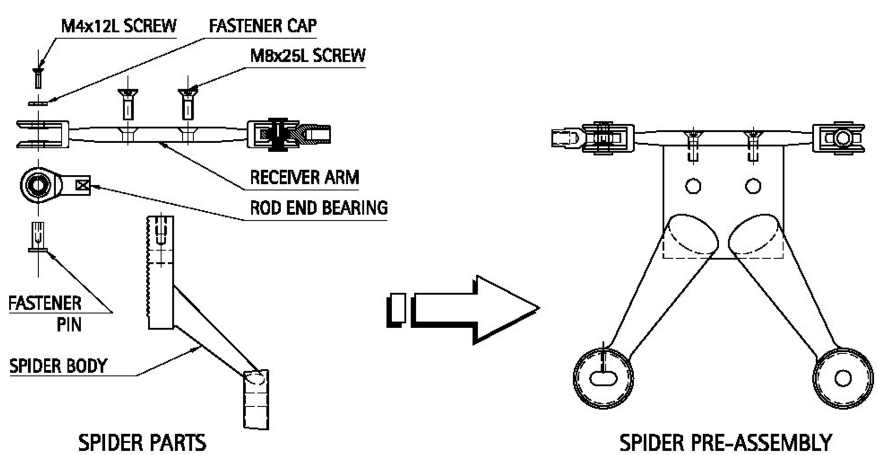


Fig. 4.1.1(a): Assembly of Spider Fitting.

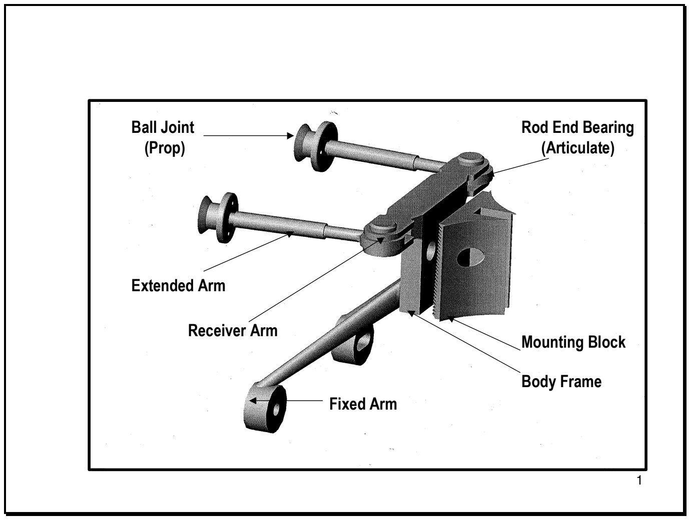


Fig. 4.1.1(b): Isometric View of Improved Spider and Mounting Block.

Appendix B1-6 to B1-14 shows the spider fitting listing for the entire project and the fabrication drawings for the spider and its components.

4.1.2 Steel Mullion Fabrication

Cutting the steel plates using oxy- acetelyne torch leaves a tolerable inaccuracy in establishing a perfectly straight edge to shape the mullion. For this reason, the mounting block positioning shall compensate the marginal discrepancies by maintaining a constant 147mm distance from the center of the two fixing holes at both end of the mullion to the surface of serration of the mounting block.

Although the spider fittings are designed to cater in-out adjustment of up to 10mm, it is still best to apprehend whatever discrepancies that are perceived during fabrication of the mullions and which can be practically corrected rather than to throw all the discrepancies to be taken care of by the articulating props. With the precise alignment of the mounting blocks, the adjustable props will just take care of the in-out misalignments of the overall plate mullions as they are installed on the pavilion structure.

Concerning the corner mullions where the mounting block follows the bi-axial slope of the mullion, the spider arm fittings are designed to cater this intricate slope condition and therefore no exception is necessary for this case. The serration shall still be perpendicular to the longitudinal axis of the mullion plates and not necessarily be parallel to the horizontal plane.

4.1.3 Steel Mullion Installation

The 5M series of mullions are delivered to the site without their top fasteners holes, in this manner the installers can verify the position of the roof level SHS Hoop, and facilitate the punching of the top fixing hole of the mullions to suit the actual site condition.

The mullions shall be installed to the pavilion hoops from top down to the base, that is from 5M to 4M, 3M, 2M and 1M series (Fig. 5.1.3). Anticipating a considerable deflection of the pavilion tree and the hoops after installation of the glazing system, appropriate tensioning provisions shall be carried before the installation of mullions. (See Fig. 4.1.3(a) for Mullions Layout)

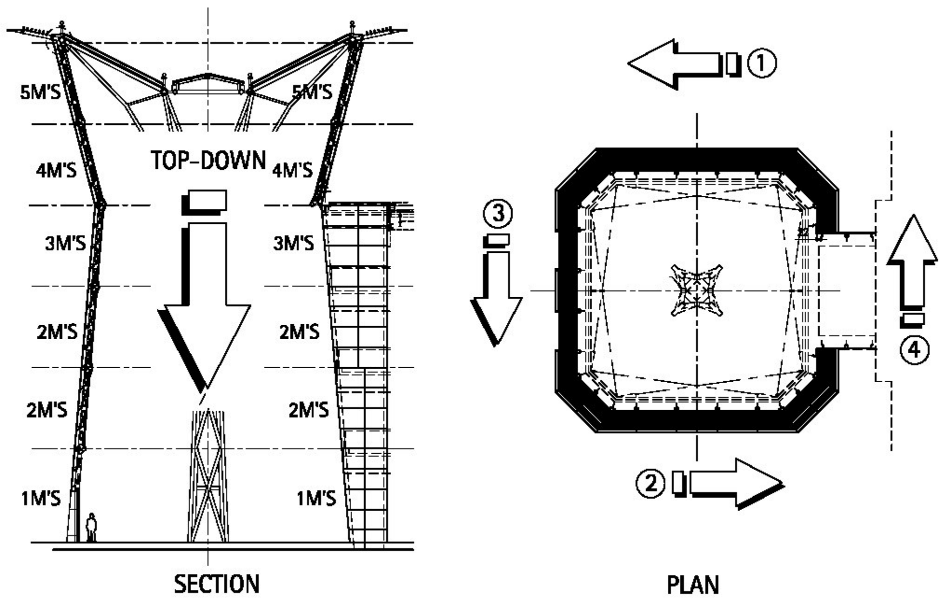
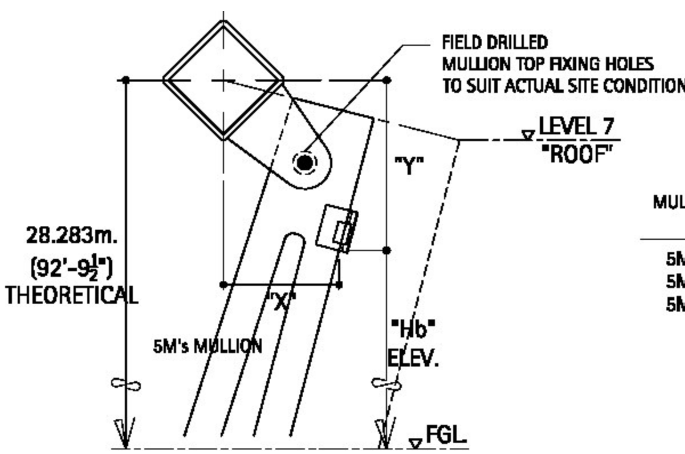


Fig. 4.1.3(a): Installation Sequence of Steel Mullion Plates

Prior to installation of the 5M series of mullions, the installer shall check the actual site elevation of the roof SHS hoops. Based on this, the upper fixing holes of the mullions shall be field drilled or punched to suit the estimated final elevation setting of the mullion (i.e., after sagging due to the mullion, spider, and glass weights). The elevations are measured from the FFL to the lower right angle intersection of the mounting block with the mullion as shown herein:



MULLION	ELEVATION "Hb"	THEORETICAL DISTANCES "X"	"Y"
5M1	27 825mm (91'-3½")	249mm (9 13/16")	458mm (1'-6")
5M2	27 816mm (91'-3 1/8")	262mm (10 5/16")	467mm (1'-6 3/8")
5M3	27 829mm (91'-3 5/8")	243mm (9 9/16")	454mm (1'-5 7/8")

Fig. 4.1.3(b): Site Setting-Out of 5M Steel Mullion Plates

Similarly, the set-out for the rest of the mullion plates are measured from the respective lower right angle intersection of the mounting block with the mullion, i.e. 4M, 3M, 2M, etc.

Chapter 5 Processes and Materials

5.1 Casting Processes

5.1.1 Basic Process and Purpose

The basic principle of surrounding a wax pattern with a liquid mold material, allowing this mold material to harden about the pattern, melting the pattern out by heat, and then casting molten metal into the resulting cavity, is one of the oldest of human arts. Evidences of its use by primitive peoples exist in many parts of the world. These primitive users, as well as more refined artisans of the Middle Ages such as Benvenuto Cellini, had to make each individual wax pattern by hand forming. This was suitable for ornamental objects, or other castings, which did not have to be identical. But the lack of a means of producing large quantities of uniform wax patterns obviously limited the process to this type of use.

Two types of pattern dies are in common use today. If the design is such that it can be quickly produced by standard milling and lathe operations, a steel die can be either hubbed or machined and assembled. Since most investment casting have intricate or irregular shapes, the more usual practice is to make a metal master, an oversize replica of the final casting, which is then used to form a die in a soft metal such as a zinc alloy or one of various tin bismuth alloys. The latter type of die will wear faster than the steel die, but it is possible to replace it by the use of the same original metal master.

When large quantities are involved and the design is such as to justify the die cost, patterns can be made of various types of plastics instead of wax. This lowers the unit cost of the pattern considerably, since a faster die operation can be carried out in the automatic plastic machine than with hand-operated wax die.

After the wax or plastic patterns are made, they are attached to wax bases and runners in order to produce an assembly for the casting mold. This wax assembly is then mounted on a base plate and surrounded by metal tubing which is bonded to the base plate to make a watertight seal. The mold material known as investment is then poured into this flask. For nonferrous castings, this material consists of various powder combinations bonded with plaster of paris. For steel castings, plaster cannot be used, and the bond is ethyl silicate, sodium silicate, phosphoric acid, or some similar chemical. To secure a smooth surface on the casting, the wax pattern is usually dipped in a thick slurry several times so that a shell hardens about the pattern. A backing-up material of much coarser mesh can then be used to fill in the rest of the flask.

This method of applying the ceramic mold material to the pattern is one of the points, which distinguish investment casting from other foundry techniques, which require molds made of two or more parts. (See Appendix B1-15, 16,17) for spider molds) the mold material thus "invests" the pattern completely in the literal sense of this word, meaning, "surround" or "envelop". Hence the name of the process.

Once the ceramic investment material has hardened, the molds, still containing the wax patterns, are subjected to heat in order to melt and remove the wax. This wax can usually be reclaimed and refined for further pattern use. After the wax has been removed and the mold has been cured at the proper temperatures, they are removed from the ovens and made ready for the actual casting operation. The simplest way to carry this out is to put the molten metal into the molds by gravity, but in practice various means to assist the flow of metal are used because of the relatively thin sections of castings that must be fed.

Molds can be spun in a centrifuge into which the metal is poured centrally and flung radially to fill the mold; or they can be placed on tables where a vacuum suction will remove air through the permeable investment materials in advance of the incoming metal; or they can be clamped to melting furnaces, which are then inverted, sometimes with the addition of air pressure behind the molten metal to give a greater head.

However the metal is introduced into the casting molds, the castings cannot be extracted without completely destroying the molds. This is usually done by vibration, sandblast, or chemical dipping. Individual castings are then cut off the runners and subjected to any secondary operations required. The manufacturing process is controlled throughout by careful dimensional and metallurgical inspection, the stringency of which depends upon the requirements of the individual casting. (See Appendix B1-18 for sequence of Investment Casting)

5.1.2 Area of Application

The labor cost of making both the patterns and the molds in investment casting is expendable. This is a basic feature of the process, which explains the fact that its unit costs are usually higher than those of other foundry techniques. In die-casting, no such expendable items must be used. In sand and plaster casting, the pattern can be reused, and only the mold is expendable. In permanent-mold techniques, the mold itself is reused many times.

Investment casting thus requires more labor and materials than other casting processes and cannot compete with them in unit price if they are able to deliver parts of satisfactory quality, sufficiently accurate to use. Investment casting finds its application when there is need for:

1. Metal alloy, or quality, unobtainable otherwise.
2. Complex design, requiring costly machining or assembly.
3. Small-quantity runs, where low tooling cost of investment casting may justify its use.
4. Pilot runs for design trials before building costly forging, die-casting, or automatic-machine tooling.

The tooling cost of investment castings is primarily determined by the complexity of the design and the tolerances, which must be maintained in critical dimensions. On the other hand, the unit cost of the investment castings themselves is not greatly affected by complexity, and a very intricate piece can often be made for approximately the same price as a simple piece of the same size. Size, however, is most important in determining unit price, and the larger a casting, other factors being equal, the more rapidly will it become cheaper to make it by alternate means. In general, it might be stated that quantities in excess of 20,000 units can be economically made by investment casting only when they are of optimum design and size for the process, as explained in the sections that follow.

The considerations mentioned above about quantity limitations do not apply to special alloys, which are very difficult to fabricate by other metal-forming processes. In such cases, investment casting offers the only presently known means of producing intricate forms.

5.1.3 Advantages and Limitations

It was mentioned that three basic factors determine the suitability of investment casting for a particular use.

5.1.3.1 Size

Both the over-all dimensions and the greatest concentration of weight or mass have marked effects upon the suitability of investment castings for a given design. So many operations are involved in the process and the materials used are subject to so may variables that a certain range of variation must be expected in the production runs of any investment casting. This range is such that as the part increases in size, the dimensional accuracy comes closer and closer to that of other foundry techniques.

5.1.3.2 Complexity

Although increasing size and thickness rapidly add to the cost of investment castings, the same is not true of the complexity of design. A casting of intricate shape, is no more difficult to produce than a simple geometrical shape. Therein lies the advantage if this process over automatic machine-tool operations. He most successful applications of investment casting are those in which design complexities exist which make machining operations very costly. Complex assemblies components can often be combined into a single investment casting.

As noted, increasing complexity does add to die cost because the shape of the casting must first be produced in the die or master pattern, and this requires tool-making skill. But in such cases the cost of tooling by other processes is likewise high, so that the competitive advantage of investment castings remains out-standing in these intricate shapes.

5.1.4 Materials Considerations

Investment casting produces metal which retains many of the characteristics of cast structure, but the small masses handled in each melt make possible careful control. In actual practice, most of the specifications established for government purchasing agencies can be met by investment castings. Because of the relatively small masses handled, sound metal quality can be ensured under good foundry-control conditions. However, because many heat-treatment specifications as now written are based upon forged or mill-wrought metals, care should be used before applying them indiscriminately for investment castings.

The physical properties of investment castings, made under food controls, would be midway between the longitudinal and transverse sections of the forged or rolled metal. This limitation is significant only in that the requirements of metal specifications will not be a limit to the use of investment castings. This does not mean, however, that any and all alloys are suitable for production use in the investment-casting foundry. Because of the fine details and thin sections, which are characteristic of many investment castings, the metals selected must have good foundry properties. They should be fluid, uniform in dimensional shrinkage within a fairly wide range of pouring temperatures, and free from tendency to react chemically with the air or ceramics in the investment mold.

Because of the short history of this process in industrial use, changes in techniques are occurring rapidly, and no two foundries may agree completely on all the details of production at any one time. It is therefore recommended that the final design of a part, which offers any unusual difficulties, be carried out in a consultation with an experienced investment-casting engineer.

5.2 Machining Process

Some of the machining processes required in producing the spider fittings, ball-joints fittings, mounting block, etc includes automatic turning, automatic screw machining and milling. (See Appendix B for machining components and parts). These processes are briefly explained below:

5.2.1 Automatic Turning

Plain turning operations are basic among machining functions. Engine-lathe operations were supplanted by turret-lathe and automatic-screw-machine operations because of production economies, and today a wide variety of automatic lathes are available. Advantages of single-point tooling for maximum metal removal, finish accuracy, center turning, etc are now possible with high production speeds. The casting of spider fittings will require tooling, dies and fixtures to achieve the outcome. Some of these components will require the automatic turning process. (See Appendix B1-15, 16,17)

With ordinary, single-point turning operations, automatic cycle are useful for producing machine parts, such as automotive and aircraft piston, camshafts, transmission cluster gear, bearing races, spur and bevel gear blanks, etc. These lathes are well adapted to the machining of forgings, castings, and bars held between centers or of work supported on fixtures as well as ordinary chuck work. In general, parts, which fall within the scope of automatic lathes, would be:

Those with length or special requirements as to the accuracy and finish which can only be turned satisfactorily on centers, including work turned in preparation for grinding or other machining requiring the use of centers.

Those forged, cast, or welded which cannot be cut from a bar or fed through a hollow spindle.

Forgings, castings, etc of irregular shapes, which cannot be readily held in a chucking machines.

Those requiring machining all over or at both ends.

Those required in small quantity not within the economical range of automatic screw machines.

Automatic lathe ranges in size from units designed to handle work 12mm to 35mm in diameter by 63.5mm to 457mm in length, to units capable of handling diameters up to 610mm and length up to 2438mm and more. Powered by motors from 5hp on the small units, up to 75hp on the larger machines. Full advantage of carbide tooling can be obtained wherever practicable and maximum possible production speed assured. Automatic tool relief at the end of each tool stroke avoids scraping of the tool life and providing better finish.

Lengths, which can be turned, are necessarily limited by the carriage travel in many machines to 305mm or less, but longer lengths of turn can be readily handled by multiple tooling.

Change-over of automatic lathes is relatively simple, few models requiring any new cams or equipment beyond the tooling for each new job. Setup time is short, and flexibility is sufficient to encompass a broad field. In many cases, design changes and improvements on parts being run involve little or no cost over setup.

As with other turning operations, high machinability is an all important factor in specifying materials. To ensure maximum tool life and good finishes, materials with the highest possible machinability rating should be favored.

5.2.2 Automatic Screw Machining

Generally, automatic screw machines fall into several categories: single spindle automatics, multiple spindle automatics, and automatic chucking machines. Single spindle machines are usually designed to produce parts in rapid succession from a length of bar stock fed through a machine spindle, whereas the multiple spindle machine is available both as a bar machine and as a chucker. On the chuckers, automatically operating chucks grip cast, forged, or other single parts and carry them through the cycle, ejecting the parts on completion.

The ball-joint fitting used to hold the glass for Calpers project makes use of the automatic screw machines - single spindle machine to produce the threading process.

Several basic types of single-spindle bar machines are available. One type utilizes a cam-actuated tool turret, the axis of which is normal to the bed ways, having six radial tool positions which can be successively brought into working position and cam-fed into the end of the rotating bar to perform the desired machining operations. Front and back cross slides are also used. Turret and cross slide cams for actuating the tools on some machines are specially designed for each part produced. On the other hand, some are universal and are adjusted to suit each job.
In the automatic screw threading machines, for producing large quantities of threaded parts, the six-tool turret is replaced by a single horizontal spindle, which carries a die mounted in line with the work spindle.

From these simple types with their somewhat limited range of operations, single spindle machines available increase in size and complexity to the largest which will handle solid bar stock in diameters up to 200mm and tubing to 240mm and will turn lengths up to 230mm with one movement. Special attachments make it possible to perform a variety of auxiliary operations while the standard run of operations is being completed, thus eliminating the cost of extra secondary operations. Thus, in addition to the usual forming, facing, drilling, reaming, threading, knurling, etc, it is possible to perform slotting, milling, burring, turning, thread chasing, index drilling, and cross drilling during the regular machining cycle.

Materials, which afford easy machining at maximum speeds, provide the lowest cost parts least expensive tooling. Highest in machinability of all the steel, this stock usually, results in a minimum overall cost per part owing mainly to excellent finish and rapid cutting speeds. Where corrosion resistance is imperative and plating unsatisfactory, stainless steel of the free machining which is required in most of our case, can be used. Specification of tolerances closer than necessary inevitably reduces the maximum speed of production, with resultant needless expense.

5.2.3 Milling

Milling of metal is performed in a multitude of ways on a wide variety of machines with an equally wide diversity of cutters. Inserted or integral teeth on the cylindrical body of the milling cutter remove excess metal in small individual chips as that portion of a part is passed through the path of a cutter teeth. In the majority of cases, the surfaces generated in milling, may be classified by the basic method used. Those generated in peripheral milling are the result of cutter rotation generally parallel, while those generated in face milling result from cutter rotation perpendicular to the finished surface. Peripheral milling operations can be performed either ‘up’ or ‘down’ while in face milling operations, those two methods are usually combined. Most of the dies, components, jigs and fixtures which are used to cast the spider fittings and mounting brackets engage the milling process. Mostly, the face mill process is used as it is more economical. (see Appendix B for milling components)

Up-milling methods are widely employed in manufacture, owing to the fact that natural separating forces created between the work and the cutter tends to minimize rigidity, accuracy and safety demands. Much attention, however, has been given in down milling in recent years, and with improved machines now available, this method is gaining wide acceptance. It makes possible a considerably improved surface finish over that produced with up milling, milled surfaces being largely free from revolution marks and easy to polish. In some cases, down milling simplifies fixture design an makes possible the holding of intricate parts.

Undoubtedly, the most superior surface finish is obtained with face milling, especially where high speed milling with carbides is concerned. In addition, when compared with other types of cutters, face mills permit the greatest possible feeds and speed commensurate with maximum cutter life, and since this mills also cost the least to manufacture and maintain, they afford the maximum in production at lowest cost per part.

Normal rates of metal removal at accepted speeds and feeds common to high- speed steel cutters has long determined to a considerable extent the suitability of a material for milling. The advent of high speed carbide milling, has brought into the practical production range most of these materials, some of which can now be machined at higher rates than ordinary steels.

5.3 Glass Processes

5.3.1 Basic Float Product

The glass structures are manufactured in float glass free from impurities and discolorations. The light transmission of the glass for this project is 75% and its average reflectivity is 12%. The tolerance in the glass thickness must be less than 0.05mm.

5.3.2 Cutting

The use of a numerically controlled cutting machine is recommended for cutting the glass, to achieve a precise alignment of the edges. The edges are ground smooth with chamfers on the corners.

5.3.3 Drilling

The holes are drilled with a diamond drill bit to a co-axiality tolerance between the conical and cylindrical parts of less than 0.1mm. The base of the cylindrical hole is chamfered. It is recommended that the holes be positioned in relation to one another, and not in relation to the edges, to a precision of 0.1 mm using a numerically controlled tool. There must be no flaking or shoulders inside the bore holes. The internal surface of the hole must be smooth, with minimal roughness resulting from the drilling.

5.3.4 Toughening

The glass is preferably toughened horizontally and heated to 650°C, then carefully cooled to achieve a regular distribution of toughening stresses in order to minimize the surface deformations caused by differential cooling. This level of toughening guarantees a minimum working strength of 50 Mpa.

5.3.5 Heat Soak

Each glass sheet is heat soaked to minimize the risk of spontaneous fracture due to the sulphide and nickel content. The heat soaked process is carried out in accordance with DN18516, part 4, which specifies an 8hr process at between 280 °C and 300°C.

5.3.6 Lamination

Laminated glass consists of two or more lites of glass bonded together by a polyvinyl butyral (PVB) plastic interlayer, such as Saflex interlayer. The glass plies may be equal or unequal in thickness and maybe the same or different in heat treatment. Further, laminated glass may be used as a single lite or both lites of an insulating glass unit.

Research has demonstrated that the same common laminated glass products (same ply thickness, same glass type) behave as the unit is monolithic. (Amstock, 1990)

Calpers project uses a 19.52mm laminated glass, consisting of a 12mm lite and a 6mm low-e lite. The glass surface temperature at layup is normally slightly elevated to allow for some sticking between the glass and the PVB interlayer. A glass temperature in the range of 21 to 41deg C is typical in the industry.

5.4 Materials

Most of the metallic components of the spider system for Calpers project are made from stainless steel, which differs from standard steel in that it contains chromium. There are three common types of stainless steel: martensitic, ferritic, and austenitic; these are defined by the chemical composition of the alloy and by the heat treatment the material has undergone.

Most of the stainless steel used in casting the spiders is austenitc stainless steel-characterized by a nickel content of about 80%. Austenitic stainless steel lends themselves easily to being worked and welded. Additionally, they offer a higher level of resistance to atmospheric corrosion than other steels: the presence of molybdenum in the alloy improves not only the visual qualities, but also increases its passivity (or chemical resistance) to corrosive elements in the atmosphere.

The mechanical strength of the steels used in the building is defined by their elastic limit. Among ordinary steels, the value of the elastic limit will be found to lie within the range of 240Mpa and 360Mpa, whereas the elastic limit for the austenitic stainless steel used is 205Mpa (Dutton & Rice 1990). Other specialized stainless steel with a higher mechanical strength are sometimes used in high capacity condition.

Chapter 6 Structural Analysis

6.1 SAP 2000

SAP2000 represents the most sophisticated and user-friendly release of the SAP series of the computer programs. This is the first version of SAP completely integrated within Microsoft windows. It features a powerful graphical user interface unmatched in terms of ease of use and productivity.

Creation and modifications of the model, execution of the analysis, and checking and optimization of the design are all done through this interface. Graphical display of the results, including real-time display of time-history displacements, are easily produced. This program offers a quantum leap forward in the way models are created and modified, and in the way analysis and design are managed.

The analytical capabilities are just as powerful, representing the latest research in numerical techniques and solution algorithms. This release is available in three analytical versions that all share the same graphical user interface: SAP 2000, SAP 2000Plus and SAP 2000 Nonlinea
All of this program feature sophisticated capabilities, such as fast equation solvers, force and displacement loading, non-prismatic frame elements, highly accurate shell elements, Eigen and Ritz dynamic analysis, multiple coordinate systems for skewed geometry, many different constraint options, the ability to merge independently defined meshes, a fully-coupled 6-by-6 spring stiffness, and the option to combine or envelope multiple dynamic analyses in the same run.

The SAP 2000 Plus program adds unlimited capacity, bridge-analysis capabilities, a complete range of finite elements, and time-history analysis options. Ground motion effects with multiple base excitations can be included.

The SAP2000 Nonlinear version extends the PLUS capabilities by adding a dynamic nonlinear link element for gaps, hooks, isolators, dampers, hinges, and more. This nonlinear link element allows users to model the dynamic behavior of everything from tension-only braces in buildings to post-yield hinges in 3-dimensional frames to elastomeric bearings for bridges and base-isolated buildings SAP2000 Nonlinear version also feature static nonlinear pushover analysis capability for performance-based design of structures.

All of the programs above feature powerful and completely integrated design for steel and concrete, available from within the same interface used to create and analyze the model. The design of steel frame members' features initial member sizing and iterative optimization. The design of concrete frame members include the calculation of the amount of reinforcement steel required. Members can be grouped for design purposes, and a single mouse click on an element brings up the detailed design calculations.

The program is structured to support a wide variety of the latest national and international design codes for the automated design and check of concrete and steel frame members. The program currently supports the following steel design codes:

- U.S AISD/ASD (1989), AISC/LRFD (1994), AASHTO LRFD (1997)
- Canadian CAN/CSA-S16.1-94(1994)
- British BS 5950 (1990), and
- Eurocode 3 (ENV 1993-1-1)

The program currently supports the following concrete design codes:

- U.S ACI 318-95 (1995) and AASHTO LRFD (1997)
- Canadian CSA-A23.3-94(1994)
- British BS 8110-85(1989)
- Eurocode 2 ENV 1992-1-1(1992), and
- New Zealand NZS 3101-95(1995).

The SAP name has been synonymous with state-of-the-art analytical solutions since the introduction of SAP, SOLIDSAP, and SAP IV over twenty-five years ago. To these sophisticated numerical techniques, SAP2000 adds a tremendously easy and complete graphical user interface linked with powerful design capabilities, providing the structural engineer with an analysis and design program unequaled in efficiency and productivity.

6.2 Body Frame & Components Analysis

6.2.1 Determining Loads

Load combinations on the spider fixed arms are as follows:

- 1.4 D
- 1.2D + 1.3 W
- 1.2D + 1.3R

Vertical Load due to Glass Rotation

Additional force carried by spider's arm caused by lateral drift will be computed below.

Using a computer program to perform an iterative computations, R is computed from zero lateral to 76mm drift at a height of 5.29m, or expressing in terms of angular drift, from is $\theta = 0°$ to $\theta = 0.8°$

For each given angular arm, γ, meaning a given deformation of the sealant joint, δ, a corresponding value of modulus of rigidity, G, is obtained from the δ-γ equation.

The program performs this calculation procedures:

For $\theta = 0$ rad to 0.014rad by 0.01 rad,
Shear deformation:

$\delta x = 200.\theta$ $\delta y = 1143.\theta$

Percent Deformation:

$\gamma x = \delta x / a$ $\gamma y = \delta y / a$

Corresponding modulus of rigidity

$Gx = \Delta\delta x / \Delta\gamma x$ $Gy = \Delta\delta y / \Delta\gamma y$

Corresponding stress required for a γ% deformation

σx & σy from σ-γ equation

Horizontal shear $Vx = \delta x/a \,.\, Gx \,.\, Lx.\, T$

Vertical shear $Vy = \delta y/a \,.\, Gy \,.\, Ly.\, T$

Torque produced by Vx & Vy $T = Vx \,.\, Ly + Vy \,.\, Lx$

Reaction on spider arms $R = T / Ls$

Where Ls = horizontal distance between fixed spider arm = 2086mm

The results of the calculations showing the force carried by the spider arm due to glass rotation is presented in Appendix B2-1

Unit Loads on spider arm

Dead load of glass:

D = 1.143m x 2.286m x 0.018m x 25.6 KN/m3 / 2

D = 0.602KN

Wind load:

W = 1.14m x 2.286m x 1.36Kpa / 4

W = 0.886 KN

Vertical load due to glass rotation as an effect of lateral drift (see Appendix B2-1)

R = 1.67KN

6.2.2 Body Frame Analysis

The Finite Element Model consists of a body frame with two diagonally protruded fixed arms, and two horizontal receiver arms. The body and the receiver arms are modeled as a shell element whilst the fixed arm is modeled as a frame element.

The spider is restraint on two points on the body as shown on the model. For simplicity, the fixed arms are modeled as circular instead of oval, considering the geometric section properties of the arms. The various unit loads, i.e. wind, deadload, and R are added at the end nodes of fixed arms. As for the receiver arms, only wind load is used.

Refer to Appendix B2-2 to B2-19 for Steel Stress Check on the fixed arms and Appendix B2-20 to B2-29 for material, design property data and output for spider.

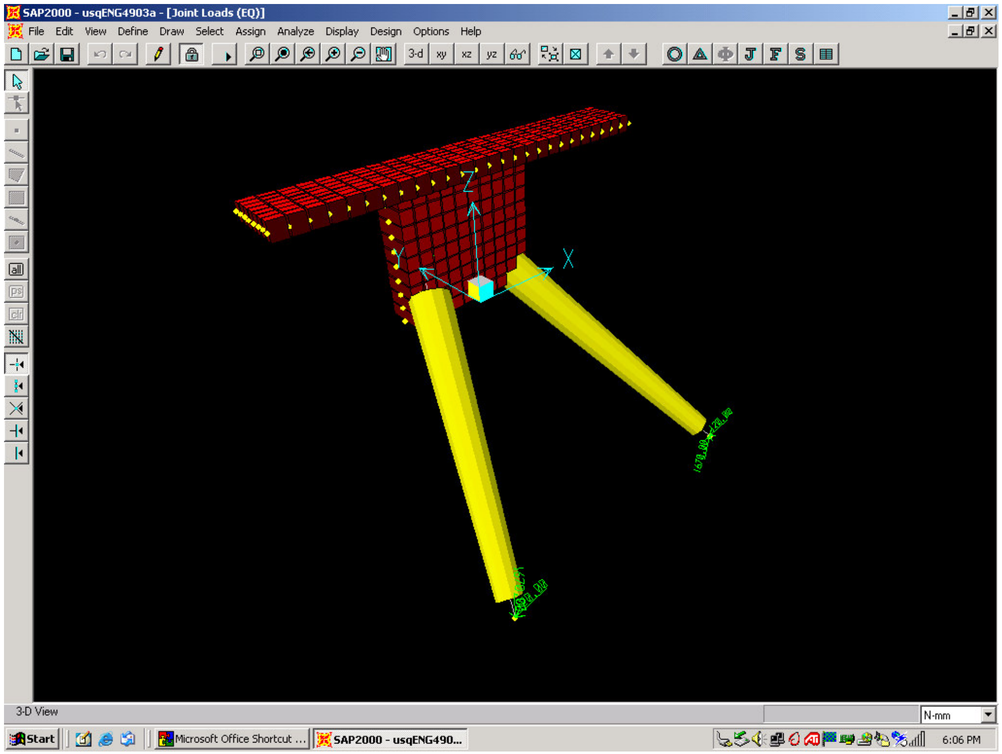


Fig.6.2(a): Unit loads due to glass and rotational effects on spider fixed arms

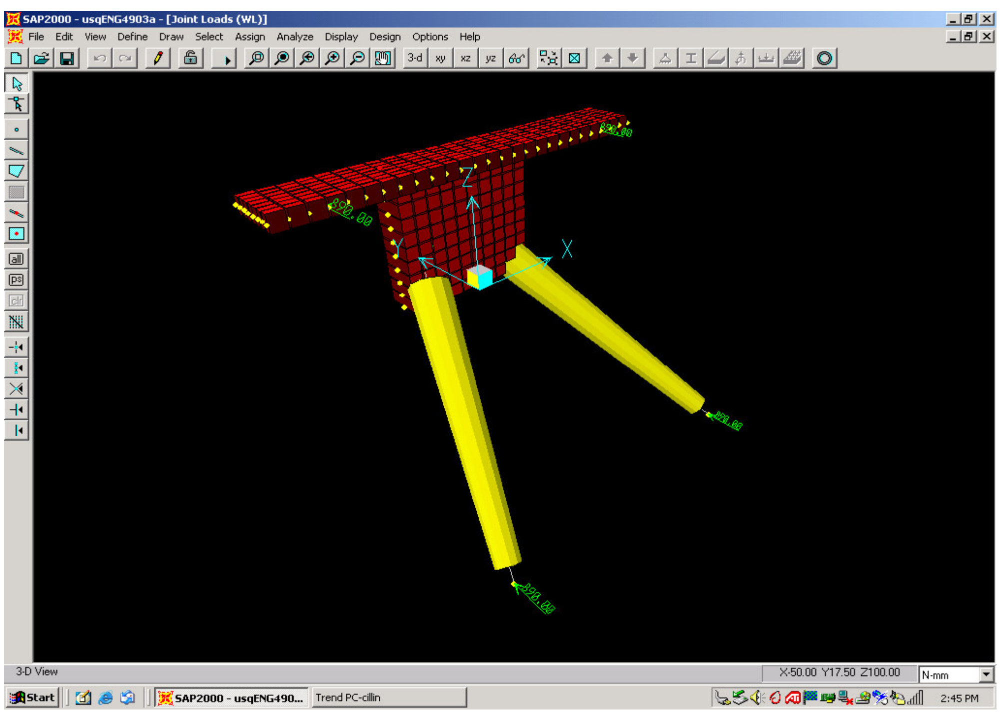


Fig.6.2(b): Unit loads due to Wind on spider fixed arms

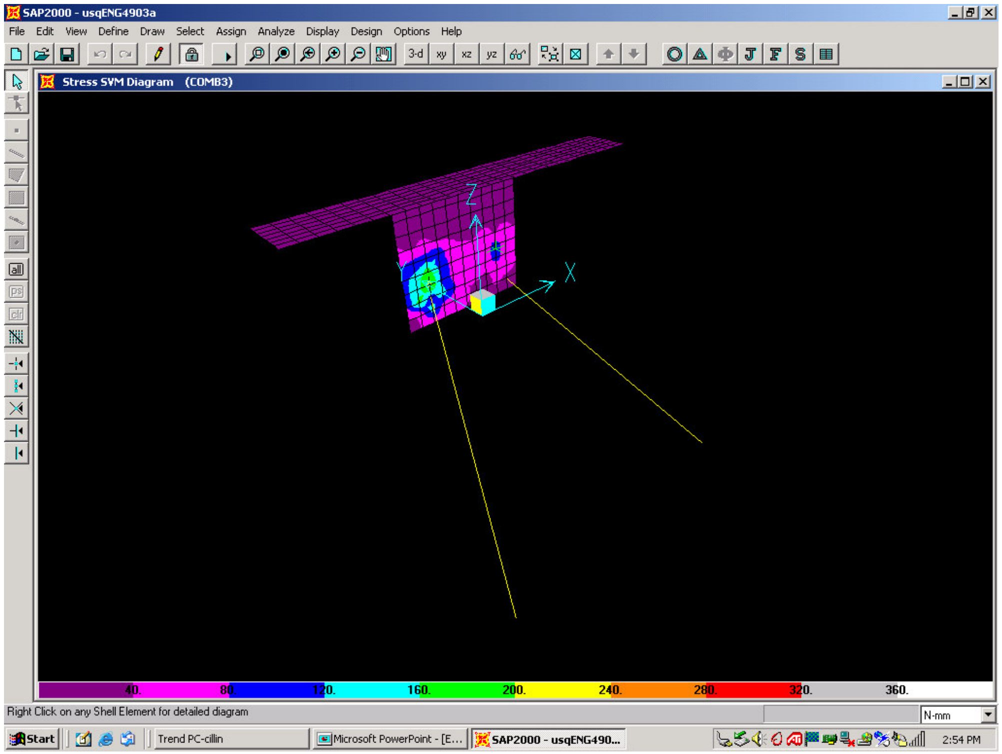


Fig.6.2(c): Stress Analysis on spider body frame

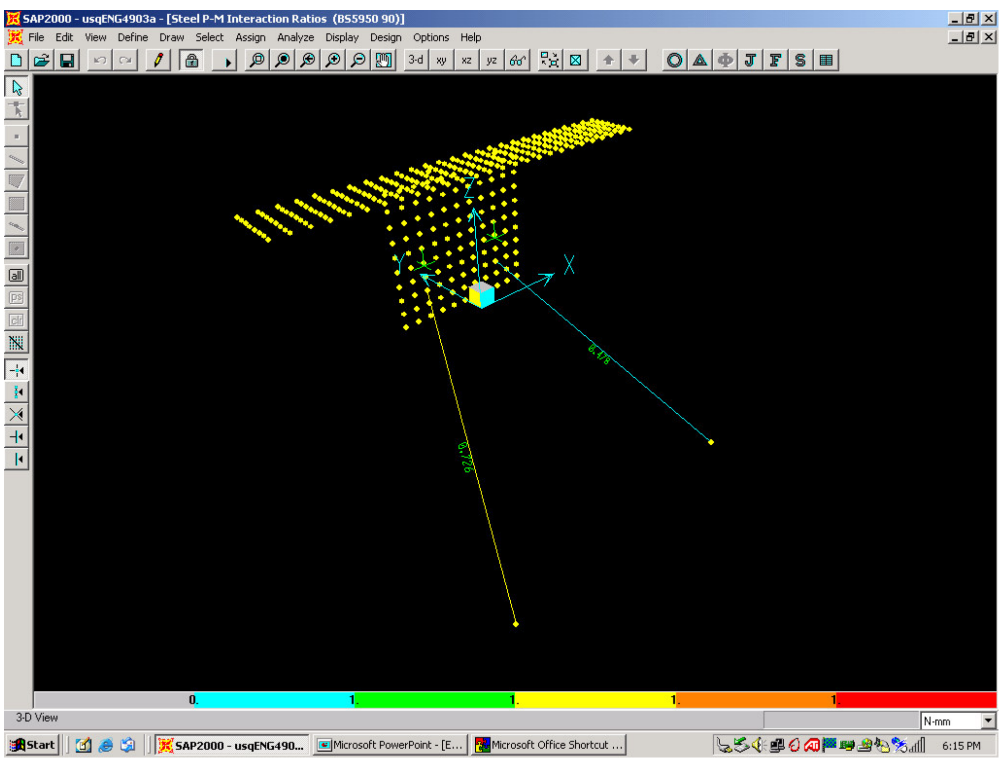


Fig. 6.2(d): Stress/Capacity Ratio on spider fixed arms

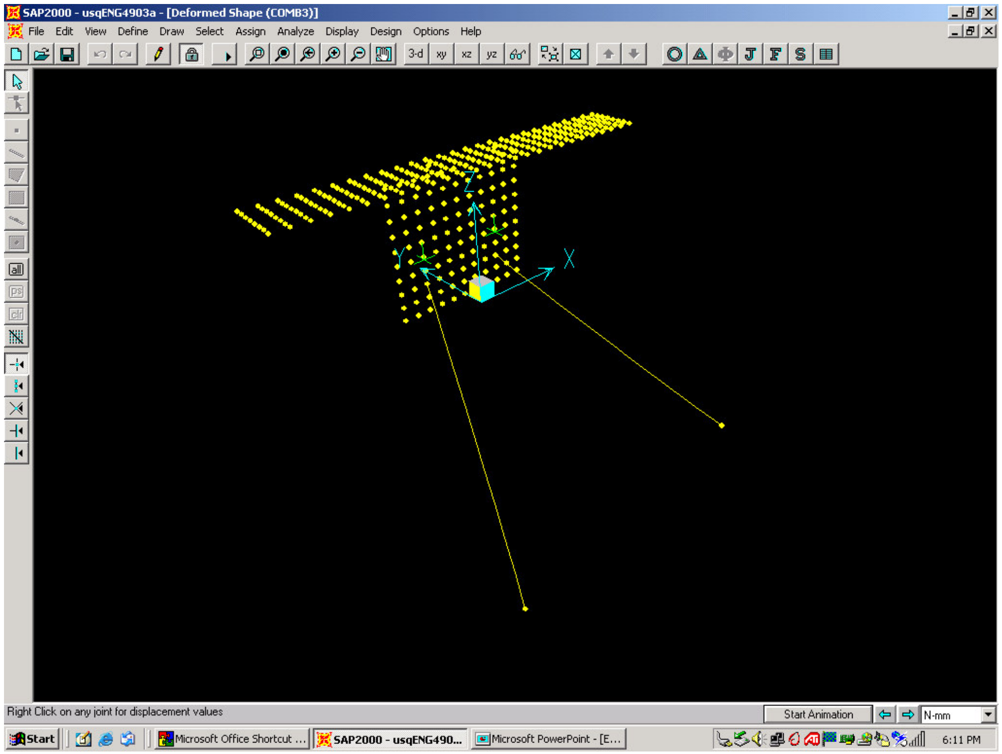


Fig. 6.2(e): Deflection checks on spider fixed arms

6.2.3 Components Analysis

The articulating arm is free to rotate in all directions, thus it will only resist the wind load.

From wind load analysis, force on each arm is

W= 0.89KN where Wu=1.3(0.89) = 1.16KN

Check M10 standard props

Compression Force, Pu = 1.16KN

Allowable Force = ∅c.Pn = 0.85 X Π (10)2 / 4 X 205MPa

= 13.69KN (o.k)

Check ∅20 Extension Rod

Similarly,

W = 1.16 KN

Compression Force, Pu = 1.16KN

Allowable Force = 0.85.Ag.Fy = 0.85 X Π $(20)^2$ / 4 X 205MPa

= 57.74KN (o.k)

Check M12 Cotter Pin

Shear force, Vu = 1.16 KN

Allowable shear force = 2 X 0.75 X Π $(12)^2$ / 4 X 205

= 34.78 KN (o.k)

6.3 Glass Analysis

Glass fails in tension or by buckling. Analytical techniques should therefore be directed towards determining the highest tensile strength under load and in determining the elastic stability of the element or framework.

It should be noted that the presence of holes leads inevitably to stress concentrations and it is important not to ignore this. Even the simplest case,that of an infinite thin element with a hole under tensile load, has peak stresses near the hole three times as large as those away from the hole.

A glass plate that has sufficient thickness to resist its design lateral pressures may still be too thin and flexible to be serviceable. Therefore, it will then be necessary to calculate deflections as well as stresses.

Haworth & Hooper (1981), Vallabhan (1983) show how non-linear plate analysis may be used to calculate stresses and deflections. Fig 6.3(b,c….j) shows the non-linear plate analysis on glass with holes.

Although calculations are useful, but in some circumstances, it is appropriate to carry out physical tests as well to convince the checking authority and the insurer that the system is flawless.

The analysis of test data requires careful consideration. Engineers are familiar with the Normal Distribution model but the Weibull Distribution model is often used in experiments involving test-to-failure because it takes into account the random nature of the causes of failure. This particularly relevant for a brittle material like glass in which the failure-causing flaw may not be located at the point of maximum tensile stress. The Weibull Distribution is described in Weibull (1939 and 1951), in Crowder et al. (1991).

III. Analysis of Wall Glass Panel

Glass Size :	2286 mm x 1143mm (7'6" x 3'9")
Glass Type :	**12t +1.52t PVB +6t Laminated Tempered Glass**
Support :	4-point supported

DEAD LOAD, DL

Weight of Glass Pane: $Wp := 25.6KN \cdot (2.286 \times 1.143 \times 0.018)$

WIND LOAD, WL

Wind Load on the Glass: $Lo := 1.20 \cdot KPa$ 24.9 psf.

For Laminated Glass : $tg1 := 12mm$ $tg2 := 6mm$

Distribute the Load by the Inertia Moment of the Glass panel

on Panel 1 : $Lo1 := \frac{tg1^3}{tg1^3 + tg2^3} \cdot Lo$ $Lo1 = 1.07KPa$

on Panel 2 : $Lo2 := \frac{tg2^3}{tg1^3 + tg2^3} \cdot Lo$ $Lo2 = 0.13KPa$

SEISMIC LOAD

Inertia Force, EQ: $EQ := 0.48 \cdot Wp$

Drift Load, R: R = check calculations.

THERMAL LOAD, T

Temperature Variation: $\Delta T := 70\,°F$

ANALYSIS RESULTS:

	Actual Values	Allowable Values	Ratio	Remarks
DL + WL + T				
Maximum Von Mises Stress:	$SVMmax := 26.66MPa$	$Fb := 50MPa$	$\frac{SVMmax}{Fb} = 0.53$	**OK!**
Maximum Shear Stress:	$SVmax := 1.02MPa$			**OK!**
Maximum Deflection:	$\delta max := 25.84mm$	$\delta a := 37.76mm$	$\frac{\delta max}{\delta a} = 0.68$	**OK!**
DL + EQ + R + T				
Maximum Von Mises Stress:	$SVMmax := 6.51MPa$	$Fb := 50MPa$	$\frac{SVMmax}{Fb} = 0.13$	**OK!**
Maximum Shear Stress:	$SVmax := 0.01MPa$			**OK!**
Maximum Deflection:	$\delta max := 0.5mm$	$\delta a := 37.76mm$	$\frac{\delta max}{\delta a} = 0.01$	**OK!**

Fig 6.3(a): Glass Analysis result for Load Combination case

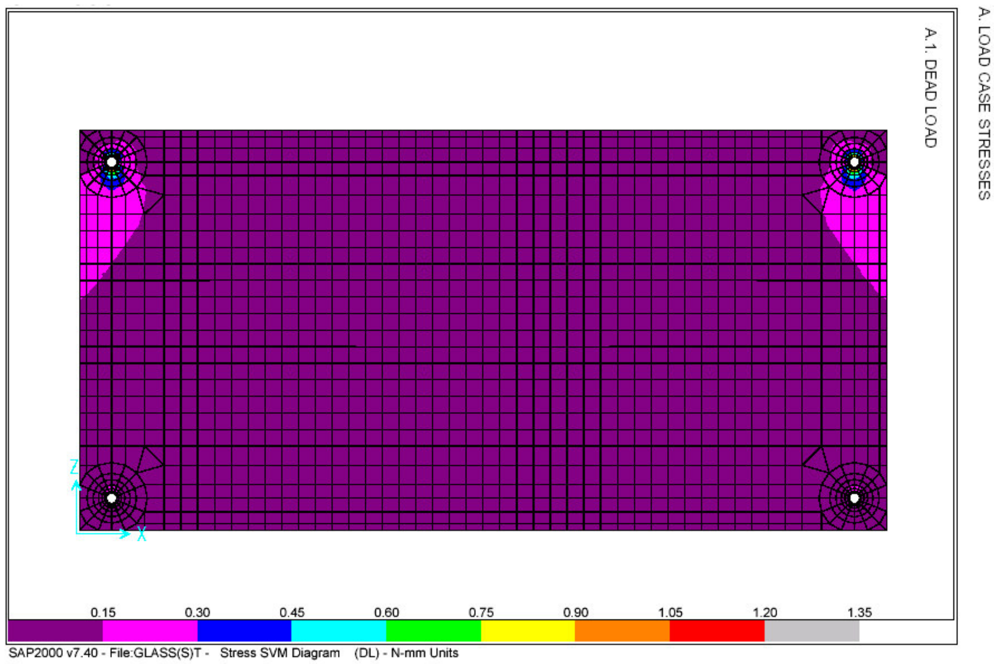


Fig 6.3(b): Glass Analysis due to Dead Load

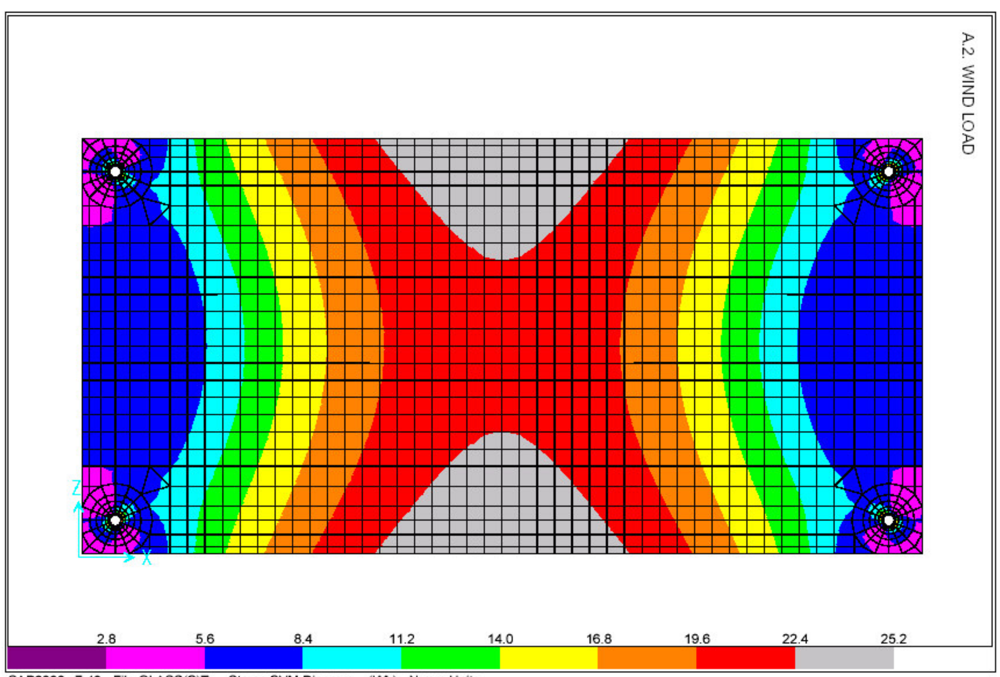


Fig 6.3(c): Glass Analysis due to Wind Load

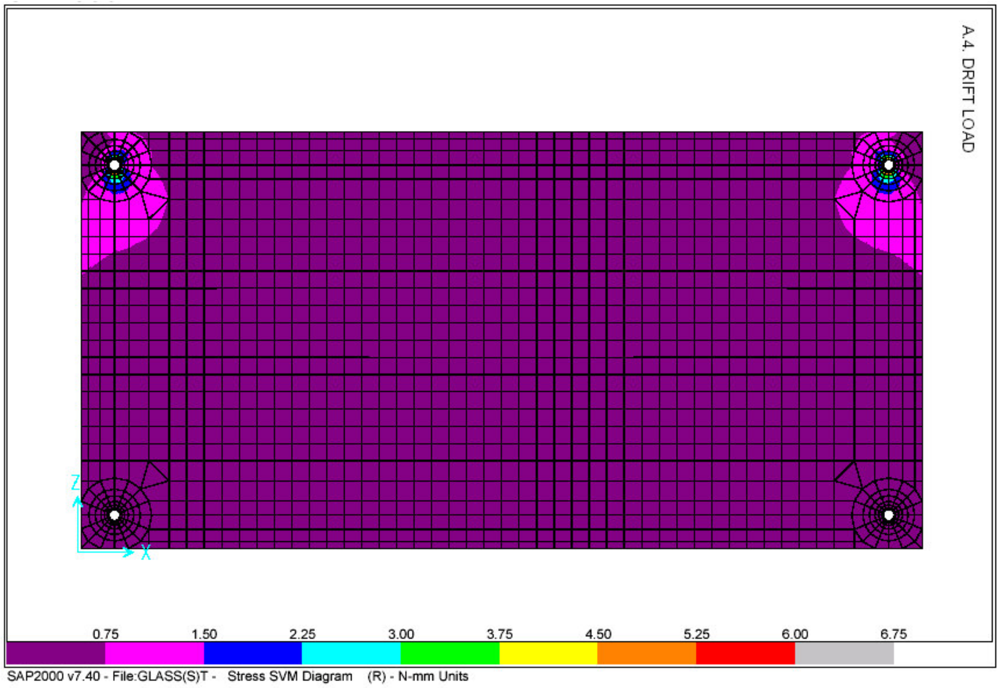


Fig 6.3(d): Glass Analysis due to Drift Load

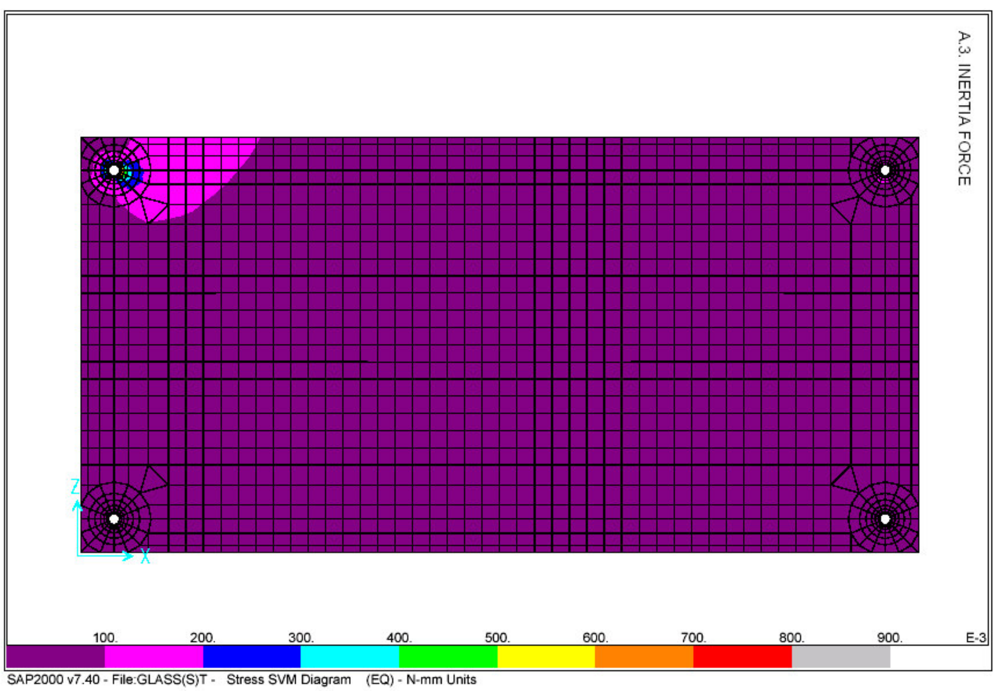


Fig 6.3(e): Glass Analysis due to Inertia force

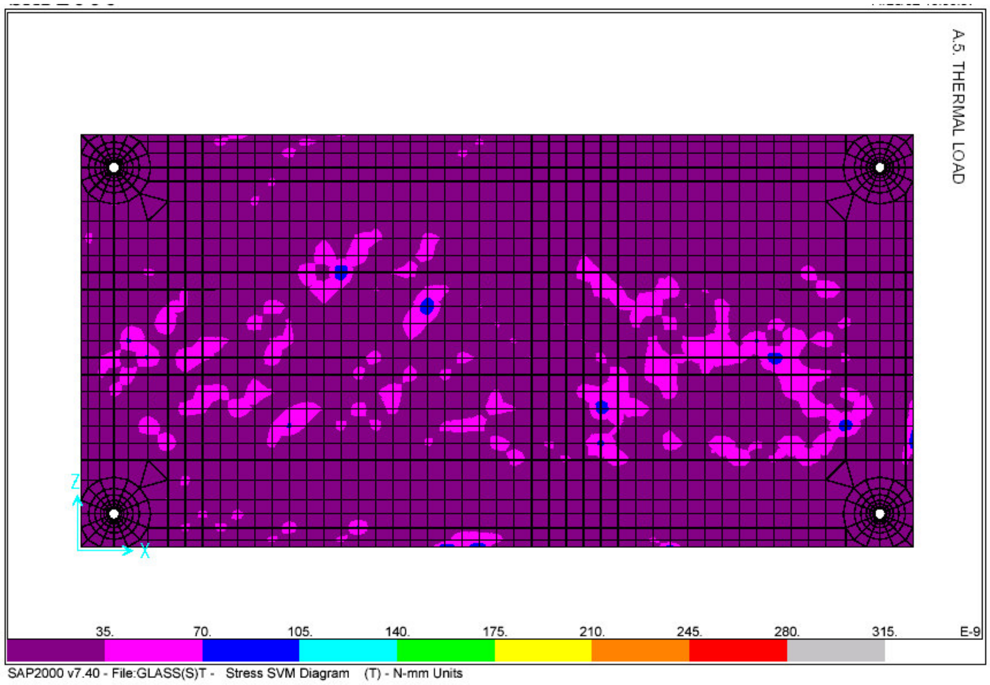


Fig 6.3(f): Glass Analysis due to Thermal Load

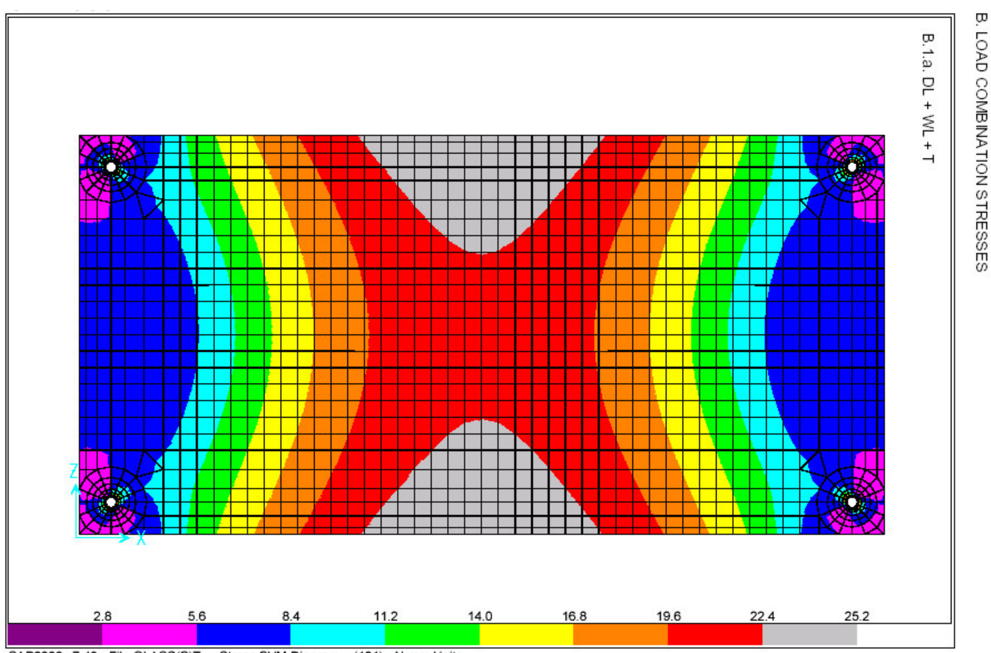


Fig 6.3(g): Glass Analysis due to Loads Combinations

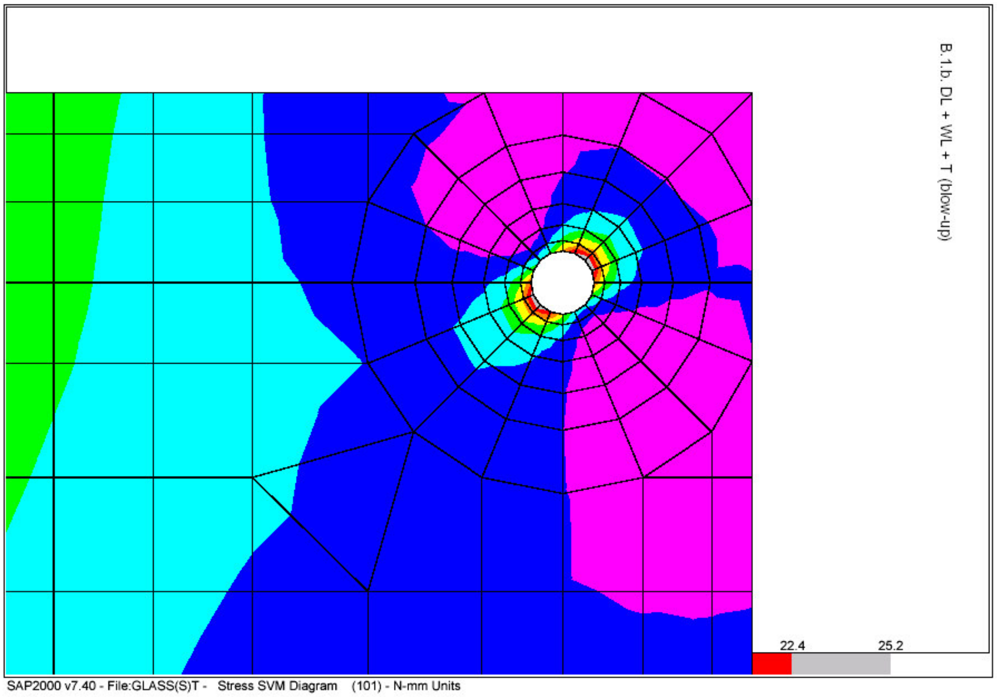


Fig 6.3(h): Glass Analysis due to Loads Combinations

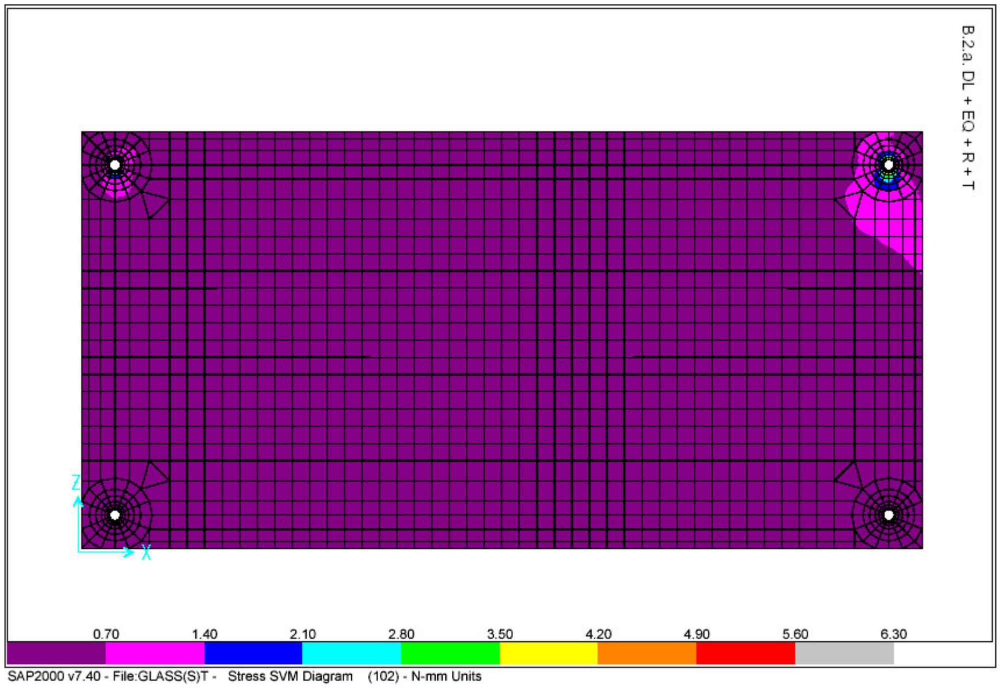


Fig 6.3(i): Glass Analysis due to Loads Combinations

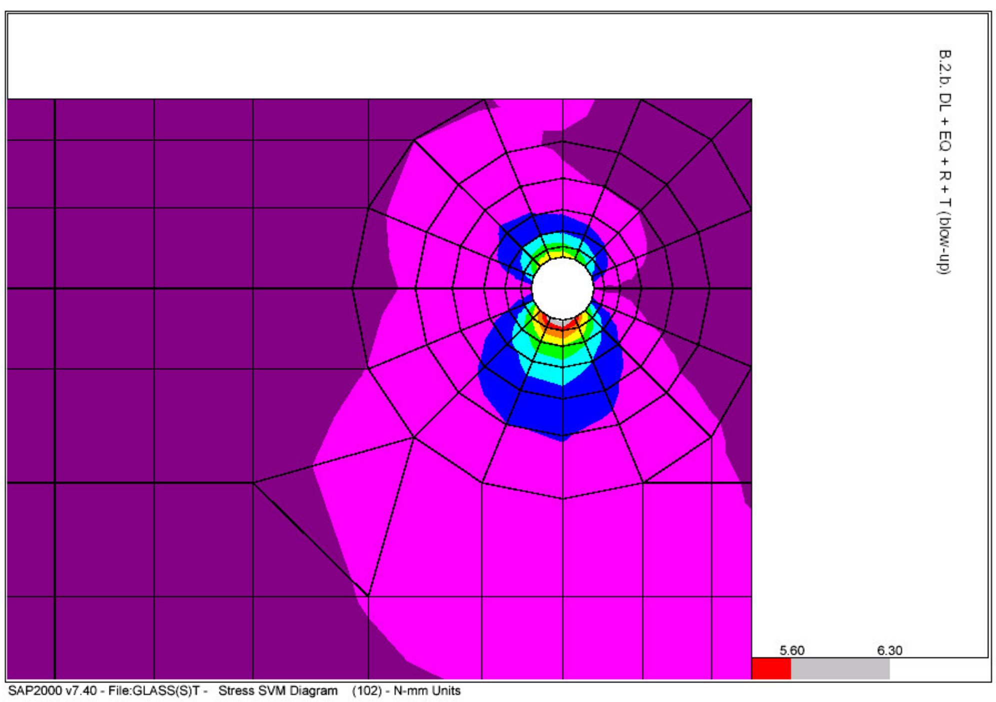


Fig 6.3(j): Glass Analysis due to Loads Combinations

Chapter 7

7.1 Conclusions

Understanding how a frameless glass wall system will perform when there is an earthquake is very important to a glass wall specialist. By understanding the behavior of the glass movement in such condition, we can prevent any unforeseen catastrophic event from happening.

Through historical data and recent studies in establishing the movement response parameters, a 76mm lateral drift over a height of 5.29m is specified for the project, which is also equivalent to 0.8° angular shift. Base on an indirect "Logical approach" and AutoCAD modeling, it is observed that the rotation of glass during drift is in the opposite direction of the mullion drift direction.

The fixed arms on the spider fitting which is required in the design for suspending the glass panes, have 'forced' the glass to rotate as the fitting shifts in relation to the mullions. By providing articulating movement on the top arms, i.e. the bottom two points of the glass held by these movement arms, the glass is free to rotate without any severe bearing stress created on the holes. The bolted connection is also designed to articulate and these ball-joint connectors further help to reduce stress on the glass holes under loads. The fitting is also designed to provide flexibility to the glass installers. It is able to compensate the errors made on the steel structure for up to 10mm in the X,Y & Z axes.

By understanding the processes involved in the machining and casting of the stainless steel fitting and also knowing their limitations, allow the components to be made with ease and reduce unnecessary cost incurred if things do not turn out as plan. Similarly, knowing the glass processes and its limitations ensure that the glass designed is safe structurally and the light and solar performance of the glass are met.

With this new fitting ideas of allowing the glass to move freely during structure drift, the dot point system which offers improved transparency and complement the evolution of building techniques can surely find its way in this new market.

7.2 Further Works

With the design in place and the forthcoming test to confirm the functionality of the new fitting, my next task is to create a design for fitting that is suitable for use both in the seismic zone and also the hurricane zone.

My recent trip to Miami, Florida has come to know that frameless glass-wall is uncommon there, and all glass façade to be built has to withstand a wind speed of up to 180mph and a 3” X 3” timber impact test.

Areas to look at include:

- Structural issue for fitting
- Structural issue on glass
- Glass connector
- Sealant to withstand high pressure
- Weatherseal at bolted connection

References

- American Society Of Civil Engineers Manual.
- The Institute Of Structural Engineers, London, 1999
- Structural Use Of Glasses In Buildings
- Standards Australia. Glass In Buildings
- Handbook of Glass in Construction (Armstock)

Appendix A: Project Specification

ENG 4111/2 RESEARCH PROJECT

PROJECT SPECIFICATION

FOR:	Heng Hern
TOPIC:	Design Of Structural Glass Fittings For Seismic Condition
SUPERVISOR:	Amar Khennane
SPONSORSHIP:	United Reliance Engineering Pte Ltd

PROJECT AIM: The project aims to design a 'Spider' for Dot point Glazing such that it is able to transfer the Windload and Deadload effectively to the structural mullions. It also allows the glass to move freely in the event of an earthquake.

PROGRAMME: Issue 01 April 2004

1. To identify the loadings and seismic drift requirements according to the specifications for a particular project.
2. To analyze the behavior of the facial glass under seismic drift.
3. To design the fittings such that it is able to transfer loads effectively to the structural mullions.
4. To design the fittings to cater for the behavior of glass such that no breakages of glass are allowed during seismic condition.
5. To design the fittings to ease installation. i.e. allow on-site adjustments in the x, y, z axes.
6. To provide structural checks on spider body, arms and props using Finite Element Software. (SAP 2000)
7. To use Solid Modeling (Solid Works) to define the actual profile and shape of fittings.

As time permits:

8. To analyze the glass size as per Architect's intent and decide on the thickness and glass combination.
9. To provide structural checks on the structural mullions.

AGREED:

_______________(Student)_______________(Supervisor)

_______________(Date) _______________(Date)

Appendix B

B.1: Supporting Information

B.2: Analysis Results

Appendix C: Codes and Standard

International Codes and Standards:

- International Convention Of Building Officials (UBC ,1997)
- American Institute Of Structural Engineer (LRFD 1994)
- American Welding society (AWS)
- Standards Australia. Glass In Buildings (AS1288)

Materials Standards:

- American Society Of Testing And Materials (ASTM)