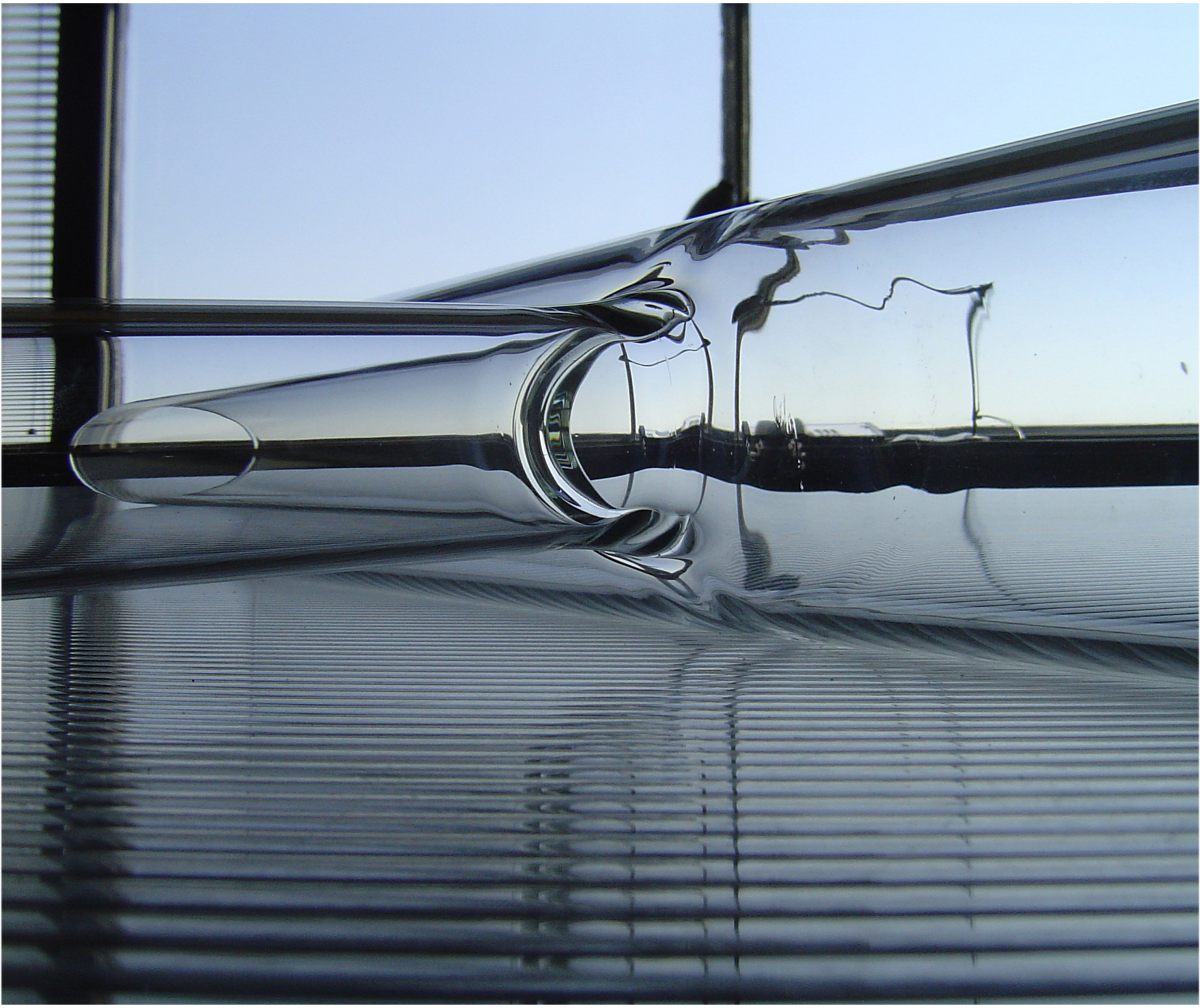
Development of a structural element of glass with glass welding processes.

Graduation report



Cecile Giezen

Development of a *structural element of glass*, with glass welding processes.

Graduation report

Cecile Giezen
Delft, January 2008

Preface

In front of you lies the final report of my graduation project *"the development of a structural element of glass, with glass welding processes".* This graduation project is done within the department of building technology at Delft University of technology. This research project consists of five important steps, namely the literature research, description of the theory, design research, experimental research and the integration of these points that leads to a conclusion. On the basis of a case-study it was possible to deepen further into the welding theme. During this process I had some reverses due to many unknown factors I had to deal with. Sometimes I wanted to solve everything at once and had to except that it was not possible, but means that I have learned a lot.

During this process, project discussions were very important to complete this project. Therefore I would like to thank my tutors, Ir. F.P. Bos, Dr. Ir. F.A.Veer and Prof.dr.ing. U. Knaack. Furthermore I would like to give my acknowledgments to G. Baardolf, for helping me making the test setups and Ir. G.J. Hobbelman for consulting me with the mechanical parts. Next to that the model and specimen making was not possible without the help of Henk Lukas and Louwers Glastechniek in Hapert.

Finally I would like to thank my parents and of course Ralph, who always were present at times I had to go through big changes during my life.

Delft, January 2008
Cecile Giezen

Summary

Glass is transparent and that is its advantage in contradiction to other building materials. Nowadays glass has a very important position in architecture. We all know glass used for windows, but the constructive possibilities of glass are much greater. Although its brittle character, glass columns and beams aren't a new concept anymore.

Flat glass is the most common applied geometry used in the building industry. Particularly with a material like glass it is possible to make a great variety of forms. When bonding two glass elements, adhesives and metal or polymer joints can be applied but it can also be done by the so called glass welding process. Thermal deformation of glass is using the typical characteristics of glass. Glass is easy to deform into every shape when heating it up till its deforming temperature. The viscosity of the glass decreases and by means of bending, blowing and connecting, it can be shaped into every form. This process is well known in the lighting and chemical industry. However these elements are small in contradiction to the building scale.

Glass welding has not been used up until now for load bearing glass elements in de building industry. This is because of the almost inevitable problems. Both during fabrication and after installation unevenly distributed temperature stresses arise in the joined elements.

In general materials that are subjected to temperature changes, the atom structures changes. Therefore the coefficients of thermal expansion and the thermal conductivity are very important values for the creating of a welded joint. Connecting different kind of glasses results in stress, due to difference in shrinkage. The thermal conductivity of glasses is very low; for this reason glasses that have a low thermal expansion are easier to weld. Soda-lime glass is normally used as flat glass in the building industry. This glass had a high coefficient of thermal expansion and difficult to weld. However borosilicate glasses have a low coefficient of thermal expansion and are in contradiction to quartz glass much cheaper.

An existing facade structure of the faculty of architecture in Delft is the starting point for researching the possibilities of the application of glass welding. In the entrance hall the low rise blocks and the high rise block are separated by glass facades. The steel space trusses accommodate the wind loads on the glass facade.

The new concept involves a curtain wall with a load bearing welded glass construction. The posterior construction is build out of tubular glass elements, because flat glass is less common in the technical glass industry and difficult to weld. The construction consists of star-shaped welded elements with a height and width of 1,8 meters. This size limitation is dependent on the manufacture possibilities. The glass elements can be piled up and next to each other and form a net-structure. With the help of cables the tensile forces are accommodated and the structure is set stable.

The total construction is built out of elements. The joint between the elements is pretty complicated. It should be demountable, if one element fails it must easily be replaced, and it must accommodate shear forces, torsion and compression forces. A joint based on the torque bicycle principle is designed, to meet to all these requirements. The inner construction of the joint consists of crenulated heads and the outer construction consists of cap for the aesthetic finish.

Earlier research by ir. F.P Bos on small butt-welded borosilicate glass tubes show that welded glass is not by definition weaker than intact glass tubes. In this research elements with sizes relevant for building elements are tested. With the help of a 4-point bending test centrally welded glass tubes of 700mm were tested. To research geometry freedom t-joint specimens were tested. A compression test was performed by placing on the small arm a pressure force and a moment test was designed by adding a force load to create a moment in position of the welded joint.

Geometrical inspection was done to evaluate the specimens. The size of the heat effected zone and the accuracy of the dimensions were inspected. The finite element method and strain gauges were used to compare the results of the experiments.

Nineteen butt- welded specimens (lxdxt 700x40x3.2) were subjected to a 4-point bending test. The support separation of test was manually set on 600mm and the force source separation at 200 mm, 1/3 of the span. Data of the specimen and the test are inserted in the test program TestExpert and the specimens were tested in a Zwick Z010. Except one, all specimens failed at the maximum stress zone, of which two failed at the weld. The obtained bending failure strength is comparable to soda-lime glass, but lower than the failure strength from earlier research. This has to do with the scale effects.

The t-joint specimens, a total of 8, were tested with the help of a compression test. The main tube (lxbxt 700x80x5) was supported at the ends, with a span of 600mm, while a force was placed on the arm (lxbxt 350x40x3.2). An auxiliary construction was needed to avoid the main tube form slipping to the side. Six of the eight specimens failed at the support. FE-analyses also prove the highest stress at the support. In this case the support was designed as a pin support. The stress calculated in de centre of the main tube is lower than the actual failure strength. Finally the calculated stresses are matched to the FEM-output.

The last experiment involves a moment test. A force is placed at 250mm of the arm. This results in a moment where the glass tubes interfere. A steel auxiliary construction was used to fixate the glass main tube. The results of this test have a smaller spread than the 4-point bending and compression test. However it is hard to compare different kind of experiments with each other, due to uncertainties.

From the experimental research can be concluded that the welded part of the glass tube is not per definition weaker than the untreated glass tubes. The size of the heat effected zone, created during welding, has not any influence on the strength. Failure is not preferred at the weld or in the heat effected zone.

Glass welding provides great design possibilities for architects. Opportunities are there to apply welded glass, however limited to certain sizes. The presented facade structure in this research might be a good solution for introducing glass welding. Although more research need to be done to ensure safety and residential strength.

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H1. Introduction

~ Glass[1]

A brittle and transparent solid
A window pane
A container for holding liquids while drinking
An object of glass (in general)

As we all know glass is a solid and transparent material. The most funny thing is that people are looking through and surrounded by glass everywhere. It doesn't stick to windows only. Imagine that we continuously look through glass, like spectacles, cameras, televisions, car windows and mobile phones. We live in a transparent world.

Glass has been used for many centuries in architecture. It creates space and brings light from outside and a view to the world outside. The time of using glass only as window glass has passed by. Nowadays complete buildings and facades of glass arise in the cityscape.

This all was poet Paul Scheerbarts vision. In his book G*lasarchitektur* in 1914 he wrote; '*To elevate our society to a higher level, we must change our architecture. And this is only possible, if we deprive the spaces of their closed character. Introducing glass architecture is the possibility. The light of the sun, the moon and the stars will not enter only by a few windows, but through as many walls as possible.'*[2]
This text was dedicated to Bruno Taut, a German expressionist architect, who built the glass pavilion for the Werkbund exhibition in 1914. These ideals of glass culture proposed by Scheerbarts and Taut, illustrate the true potential of glass.

Almost a century later constructing with glass is still an inspiring item. Detailing, the unreliability of failure, dealing with the unreliability and the calculation methods are still the main questions in constructing with glass. These days glass is still connected with steel frames or bolts, but the attention to reach optimal transparency is to leave these supporting things out. A way to reach this is to create a material that is transparent and structural as well.

A possibility of connecting glass is through the welding process. Theoretically it is possible to make separate glass elements and then weld them on the building site. But practically it is not that simple…

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[1] Koene, M.J. Drewes, J.B. (1992/1993) Wolters woordenboek Nederlands. Wolters-Noordhoff bv, Groningen
[2] Frampton, K.(1995) Moderne architectuur, Een kritische geschiedenis. SUN, Nijmegen,p145

H2. Development of a structural element of welded glass

2.1 Topic

Glass is transparent and that is its advantage in contradiction to other building materials. Nowadays glass has a very important position in architecture. We all know glass used for windows, but the constructive possibilities of glass are much greater. Although its' brittle character, glass columns and beams aren't a new concept anymore.

It may be a utopia to create a building completely out of glass, but some architects attempt to reach optimal transparency. It is a challenge to research in what way the highest level of transparency can be reached. This may lead to buildings with a lack of architectural expression, because the form freedom of glass used in the building industry is pretty small. It is limited to (curved) glass sheets or profiles.

Particularly with a material like glass it is possible to make a great variety of forms. To proof this we don't have to search far, just look in the kitchen; like wine glasses, ovenproof dishes and vases. But also glass that is used in the chemical industry, where experimental setups are designed and the most difficult pieces of glass are melted together.

What directly strikes you is that these elements are small in contradiction to the building scale. To joint two glass elements, adhesive joints are widely used. The forces are transmitted by mainly metal fixings and this will also reduce the construction's transparency.

Bonding two glass elements can also be done by the so called glass welding process. Thermal deforming of glass is using the typical characteristics of glass. Glass is easy to deform into every shape when heating it up till its deforming temperature. The viscosity of the glass decreases and by means of bending, blowing and connecting it can be shaped into every form.

Welding has not been used up until now for load bearing glass elements in de building industry. This is because of the almost inevitable problems. Both during fabrication and after installation unevenly distributed temperature stresses arise in the joined elements.

2.2 Background

When glass is fabricated, the basic ingredients sand, sodas and calcium are melted together and will become a syrupy mass. During the moulding phase the temperature is controllably decreased and the glass product becomes more viscous. When the product will be directly cooled down by the ambient temperature, the surface will become hard and locks up the, still warm and syrupy, centre. That is why heating glass, entirely or locally, will lead to internal stresses while cooling down too quickly. Therefore annealing is necessary to avoid the thermal stresses.

Up until now glass welding isn't applied in the building industry. It is mainly used in laboratory industry for small elements and the production is based on these elements. The scale of building elements is bigger and the assembling of these elements should be attuned to the production possibilities of the factory.

Another part is the safety aspect of constructing with glass. Glass in rigid state can't behave plastically and that is why it breaks spontaneously. It will not warn if stresses reach the failure stress and the deformation is not obvious enough to detect overloading. Glass is theoretically very strong, but due to small cracks on its surface and moisture the strength deceases enormously. Glass has a high compressive strength, but it is weak in tension, like all ceramics. Because of the random distribution and depths of the cracks on the surface it is hard to define one design strength for every glass piece. Research by dr. ir. F.A. Veer, "*Strength and fracture behaviour of annealed and tempered float glass*"[1] prove that there are considerable uncertainties in the literature about the exact parameters and allowable design strength. This means that the strength of glass has a large distribution. Up until now there has not been lot of experimental research about the strength of welded glass. To define a design strength for a structural element, experimental research should be done.

A research, "*The strength of welded butt joints in borosilicate glass tubes"*, done by Freek Bos[2] presents the strength of small borosilicate tubes. Butt-welded borosilicate glass tubes have been conducted on 4-point bending tests. These welded joints were in axial direction of the tube and most of them are located in the middle, but some at 1/3 of the length. There welded specimen are compared to a single piece of glass tube. The results of this research show that the welded joint was not the weakest link. The bending tensile strength of non-annealed glass is higher than the specimen without a weld. The strength of welded specimen that were annealed was a slightly lower than the one piece specimen.

In the building industry we never work with only one material. This means that connections should be made between two elements of the same material, but also between different kinds of materials. Attention to the detailing of the structural element is another important item.

2.3 Consequences

The maximum sizes of flat glass are 6x3,2 meters, due to manufacturing and transport facilities[3]. When welding of glass can be introduced on the building site it would be possible to make larger glass elements with transparent joints.

[1] F.A.Veer , F.P. Bos, J. Zuidema, T . Romein, Strength and fracture behaviour of annealed and tempered float glass, Delft

[2] F.P. Bos, F.A. Veer, (2007). Bending and buckling strength of borosilicate glass tubes, Delft.

[3] The institution of Structural Engineers Structural (1999), Use of glass in Buildings, London. SETO

This could lead to the use more form freedom of glass elements and will give architects more options of using glass, instead of the float glass panes or tubes that have been used up until now.

2.4 Research questions

In order to investigate the strength of welded glass and the possibilities of designing with welded glass, the following questions need to be answered:

2.4.1 Related to subject

- How can glass be shaped and welded?
- Is it possible to weld every kind of glass?
- What are the limits in production methods?
- What has been made with these processes?

2.4.2 Design requirements

- What are the demands and wishes?
- What are the characteristics of glass?
- What kind of element will be designed?
- And what kind of structural principle will be used?
- What are the current methods to connect glass?
- What are the visual impacts?
- What are the maximum depths/perimeters?
- What are the maximum available material sizes and profiles?
- Which loads needs the element to accommodate?
- What are the limits to the deflections of the structure?
- How will the constructional safety be guaranteed?

2.4.3 Material research

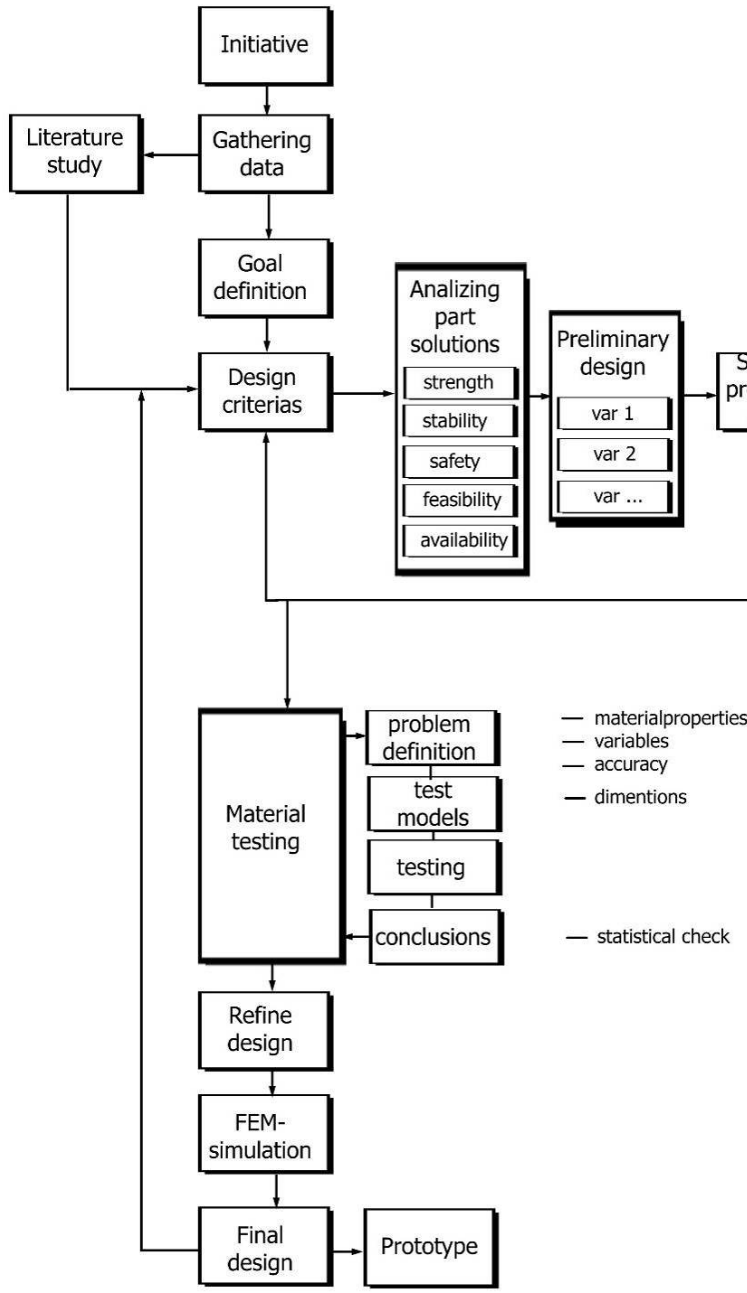
- How are the perpendicular joints made?
- How accurate are the dimensions and the thickness of the joint?
- Is there a significant difference in strength of annealed prototypes and non-annealed prototypes?
- What is de difference of the stress distribution in the effected zone of the test models?
- Is there a difference in strength or stability of the different joints?
- Where does failure occurs? In the weld or right next to it? How do the cracks flow?
- How is the visual quality of the different joints?

- **Can welded glass be used in the building industry? And how should this element, according to the hot-shaping and welding processes, be shaped and made?**

2.5 Research model

This diagram shows the undertaken steps during the research process.

Figure 2.1
Research model



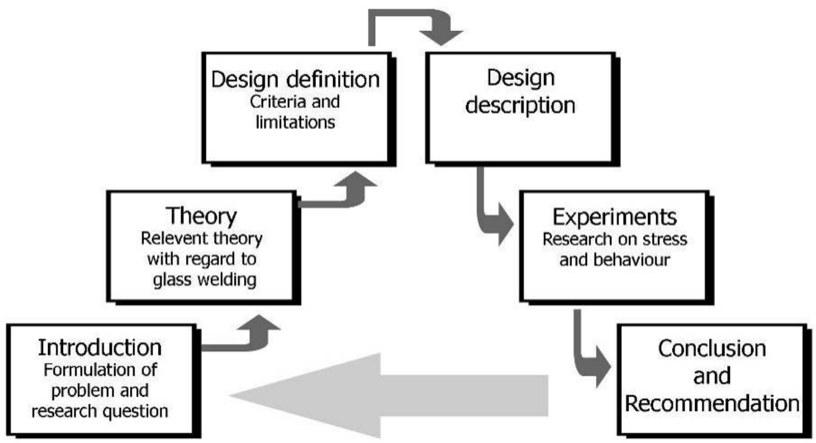
2.6 Aim of this research

The aim of this material research is to give insight into the strength of welded glass joints and define the design strength for the final design. This research should also contribute to the scientific research of using glass as a load bearing material, by giving a practical solution for the usage of glass welding techniques in the building industry.

2.7 Outline of this report

Figure 2.2 shows the structure of this report. In this chapter the research problem and aim have been outlined. The research questions should help to reach the aim. The third chapter will explain the theory of glass welding and its possibilities. Chapter four presents the starting point for the design process and in chapter five to ten the design decisions and description are written. will be about the preliminary design as a basis for the material research. In chapter eleven to fifteen the experimental research and results will be presented. In the last two chapters the conclusion and recommendations are given.

Figure 2.2
Schematic overview of the structure of this report.



H3. Theory of glass welding

3.1 Introduction

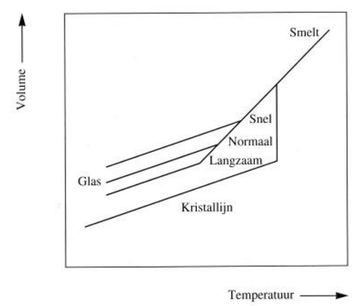
Glass is transparent and it breaks fast.

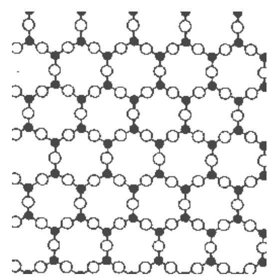
But why is glass transparent?
Glass is transparent because of the organisation of the molecules. In general there is a difference between the molecular structure of solids, liquids and gasses. There is a change in the properties of the material in these different phases such as density and strength. When a material is transformed from a liquid to a solid state, molecules will form a regular lattice and the volume will decrease. This process is called crystallisation. Crystallisation does not appear in a glass melt, because of the fast and controlled cooling down process of the melted glass. The molecules don't have enough time to create a crystal lattice, which would destroy the transparency. The molecular structure of glass is motionless, like a solid, but it contains gaps, because of the random constitution, like a liquid. Glass has a so-called amorphous structure. [1]

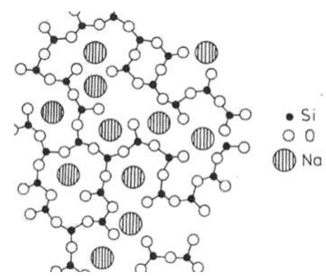
Figure 3.1 Crystallization graph

Figure 3.2 Structure Quartz

Figure 3.3 Structure soda lime glass







Transparency means no absorption, no reflection and no radiation. We consider light as a stream of photons. Each photon caries an amount of energy. Per example when light hits a bulk metal, the energy of the photon is absorbed and reradiated by "free" electrons. These electrons are free because they can absorb or reradiate light. Therefore a metal can reflect light that is falling on its surface. In glasses the electrons are not "free" in that way, that a metallic reflection would not occur. Glass absorbs light of particular wavelengths. Common glass is opaque to wavelengths at the infrared and ultraviolet ends of the spectrum, but does not absorb visible light. The structure of glass or a liquid are irregular and the individual molecules are much smaller than the wavelengths of visible lights. Light waves are not obstructed by the glass molecules, per example like water can flow through pebbles.[2]

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[1] Schittisch, C. Staib, G. Balkow, D. Schuler, M. Sobek, W. (1999) Glass construction manual, Basel. Birkhäuser.

[2] Wigginton, M.(1996) Glass in Architecture, New York, Phaidon Press Limited

The refractive index of a transparent material is defined as the speed of light though air divided by the speed of light in the material. When a light wave travels through different kind of media it will undergo a speed change. This will lead to a change of direction unless it encountered the boundary at the right angles. The light is bended in another direction. This effect is what we also see when we are laying in bath and looking through the water to our body. You will see that it deforms.

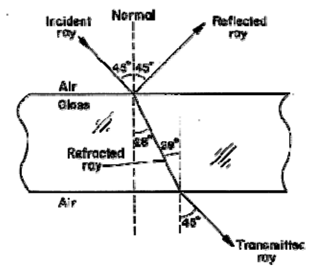


Figure 3.4
Refraction

Why does glass breaks fast?
Glass behaves, in rigid state, elastically until it breaks. That is because of the brittle character of glass. Per example steel behaves elastically. It is possible to deform a steel profile by loading it and when removing the load, the steel will return to its original form. While loading it to its yield point, it will behave plastically. First it gives a warning and permanent distortion occurs. When loading it further it will finically break. This last part, the plastic behaviour, is the big difference to glass. At room temperature glass will break without warning and has a perfect linearity of the stress-strain curve and can not deform plastically. When heating the glass till its softening point it can be formed plastically.

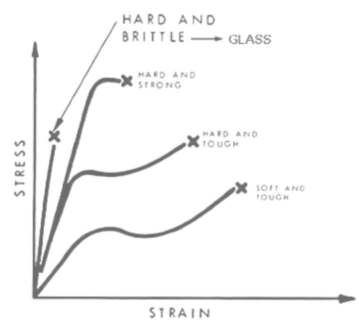


Figure 3.5
Stress-strain diagram of different kinds of materials

Glass is subject to fatigue. Cyclic loading can cause cracks to grow in materials. For many materials there exists a fatigue limit[1].

3.2 Production of glass

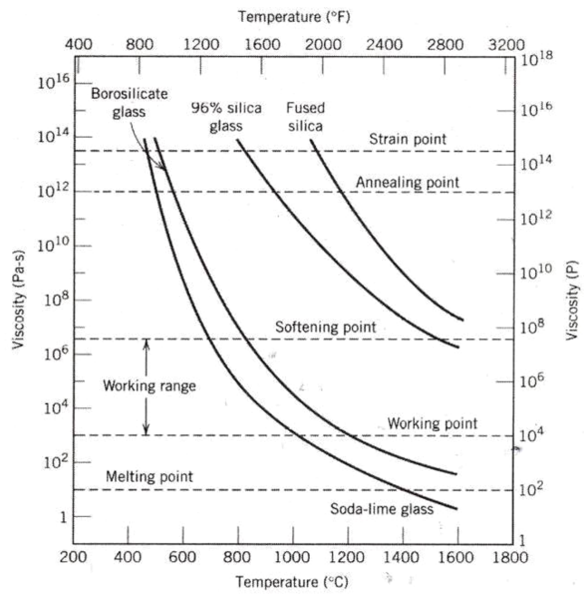
The most important ingredients for making glass is simply pure sand (silicium oxide). To meld sand, a high temperature is required. For sustainability reasons sodas (Na_2CO_3) are added to lower the melting temperature, glass

[1] The institution of Structural Engineers Structural (1999), Use of glass in Buildings, London. SETO

splinters are added to lower the viscosity and calk (CaO) and oxides like Al2O3 are added for better resistance to weather influences[1].

The ingredients, sand, soda, calk and glass splinters, are melted and mixed together at a temperature of +1500ºC in an oven surrounded by fire stones. Afterwards the mixture will be cooled down till 1100ºC. At this point it is possible to deform glass in every shape. When a liquid is cooled its viscosity normally increases. Annealing is a critical process in the manufacture of glass. Annealing is cooling down the glass product, for soda-lime glass form 600ºC to 100ºC, in controlled conditions, so it won't crack due to temperature differences and the cutting process. The relationship between the viscosity and the working temperatures of different kind of glasses is shown in Figure 3.6

Figure 3.6 Viscosity-temperature graph



3.3 Glass welding

3.3.1 Introduction

Glass welding is a process that has been used for making laboratory ware, lighting equipments and electrode tubes for many years. This process can simply be described by heating up two pieces of glass by hand or in a lathe and using the typical characteristics of glass to bond them. In the table 3.1 the advantages and disadvantages of glass welding are summarized.

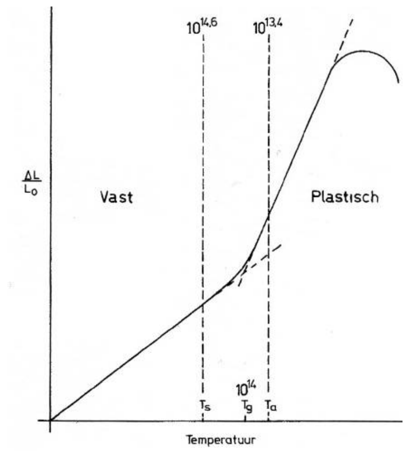
Table 3.1 Advantages and disadvantages of welded joints

Advantages	**Disadvantages**
Transparent joints	Not detachable
Stiff	Internal stresses
Complete force transmission, no drilled holes	Manufacturing methods

[1] http://en.wikipedia.org/wiki/Glass

As explained in chapter 2 in the literature part, glass changes from a solid into a syrupy mass when heating it up. There are three important points with regard to glass welding. Above T_a, high relaxation point, the material becomes plastic and deforms in short time so every present stress will dissolve. Below T_s, low relaxation point, glass becomes a solid and stresses can not be removed by internal flow. Between T_a and T_s is the transformation zone. These points define the transformation temperature, T_g. Here glass adheres to a solid material.[1]

Figure 3.7 Schematic dilatometer curve of glass



When glasses are directly bonded together it is necessary that both coefficients of thermal expansion and viscous behaviour are the same[2]. To create a bonding the parts need to be heated to the softening point. Stresses need to be avoided to make sure that no cracks could occur.

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[1] Marcus P. Borom, July/Aug 1980, De mechanische en chemische aspecten van glasverbindingen, overgenomen uit The Glass Industry, March 1978

[2] Heller, P. Ververst, J. Wilbrink, H. (1992) Vademecum voor de glastechniek, Deventer. Kluwer Technische Boeken

3.3.2 *Glass types for welding*

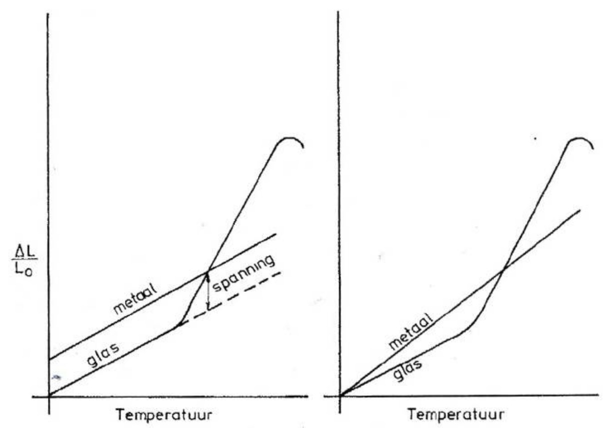
To succeed a welded joint between two glasses it is important to use the kind of glass that is suitable. As explained in the previous paragraphs, the coefficients of thermal expansion and thermal conductivity are important values for welding. The advantages and disadvantages of quartz glass, soda-lime glass and borosilicate glass are summarized in chapter 3.2 literature part.

It is possible to joint two different kinds of glasses. A joint can than be made with a transition. This transition is a special bonding of a few glass types with incremental coefficients of thermal expansion. So this makes it possible to connect soda lime glass with quartz.

3.3.3 *Glass welded to other materials*

It is possible to connect glass to glass but also to connect glass to metal and ceramics. Connecting glass to glasses or materials with different coefficients of thermal expansion, leads to permanent stresses that can not be removed by annealing or other relaxation processes. The resulting stress that will occur is dependent on the difference in shrinkage, the young's modulus and the geometry of the welded joint. To make a good glass-metal joint the coefficient of thermal expansion and contraction coefficients of both materials should be attuned to each other[1].

Figure 3.8 Attuning the coefficients of thermal expansion and the contraction coefficients



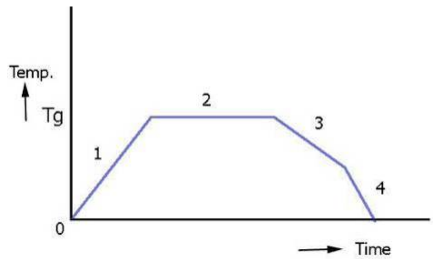
3.3.4 *Thermal stresses*

When glass is welded stresses occur in the joint. After glass becomes stiff, the internal stresses can not be removed by the internal flow. So a glass object in which stresses establish, needs to be reheated till a temperature close to the transformation temperature. The glass object will then be stress-relieved. Temporary stresses can be removed by controlled heating and cooling down processes during the deformation process. Permanent stresses in glass of the same composition can occur during the cooling down process. They can be

[1] Borom, M.P. (1978) De mechanische en chemische aspecten van glas verbindingen, Microniek No7/8 http://www.nvpt.nl/files/80-7_8-175.pdf

removed with the help of annealing. Annealing means that a glass product will be kept in a furnace at high relaxation temperature. Afterwards the product will slowly be cooled down trough the transformation area, to avoid uneven cooling down and a temperature gradient. The cooling curve is presented hereunder[1]. Stresses that are created in the glass bonding by the difference of coefficient of thermal expansion can not be removed this way. This will result in permanent stresses.

Figure 3.9
Cooling curve



1. Heating without leap
2. Relaxation zone
3. Cooling-off zone, where due to temperature gradients no new stresses may occur
4. Cooling-off zone till room temperature, where due to temperature gradients no leap may occur

Stresses occur due to the differences of the coefficient of thermal expansion. Glass is an isotropic material, which means that the material properties are the same in every direction. The length and the volume of glasses increase when temperature rises. The coefficient of thermal expansion is the most important value for the succeeding joining glasses. Permanent stresses occur when glass-glass or glass-metal is bonded with a composite material that doesn't have the same coefficient of expansion. The coefficient of thermal expansion (α) is defined by:

$$\alpha = \frac{1}{L_0}\frac{\Delta L}{\Delta T} \cdot 10^{-6} / K \qquad (3.1)$$

Temporary stresses are caused when a temperature gradient occurs in a product due to abrupt changes in ambient temperature[1]. This can be expressed as the resistance of material to thermal shock. Its resistance to thermal shock is dependent on the strength, thermal conductivity and coefficient of thermal conductivity of the material. High coefficients of thermal expansion can lead to extreme temporary stresses, so that the product breaks. A low coefficient of thermal expansion, like quartz glass has, has a great resistance to thermal shock. The thermal conductivity of a glass type is the ability to accommodate warmth and to eliminate the temperature gradient. Glass has a very low thermal conductivity and has a bad capacity to eliminate these temperature gradients. This means that when temperature changes it produces relatively high temperature differences (ΔT) between the surface and the interior. This will result in stresses (σ). These stresses are depended on the elastic properties (E) and the poisons ratio (v)[1]:

[1] Heller, P. Ververst, J. Wilbrink, H. (1992) Vademecum voor de glastechniek, Deventer. Kluwer Technische Boeken

$$\sigma = \frac{(\Delta T \alpha E)}{1-\nu} \; N/mm^2 \qquad (3.2)$$

The amount of stress present is dependent on a few factors. Per example the intensity and size of the torch flame, the glass wall thickness and the complexity of the seal itself[1].

3.3.5 Analyzing stresses

Thermal stresses can be analyzed with the help of a polarizer. Stress free glass is isotropic and light transport will be the same in all directions with the same speed. When glass is under stress, by compressing or bending it, the refractive index parallel to the stress direction will defer from the refractive index perpendicular to the stress direction. The stresses create a more ordered atomic structure and birefringence occurs. By the means of the path length difference of light (Γ) it is possible to list colours related to stresses[2].

$$\Gamma = C \cdot S \; nm \qquad (3.3)$$

C = proportionality constant in $nm.mm^2/cm.N$
S = stress in nm/cm
To convert the stress form nm/cm to N/mm^2 divide the stress by the proportionality constant.

Table 3.2 Colours to analyse the stresses in glass joints

Path length difference (Γ) nm	Colour
1st order	
100	Gray
300	Gray-yellow
380	Yellow
530	Red
575	Purple
2nd order	
620	Violet blue
680	Blue
710	Bluish green
740	Green
860	Yellow
1100	Red

The difference in 1st and 2nd order is to distinguish the colours that are almost the same. In the 2nd order the colours become more pale to almost white.

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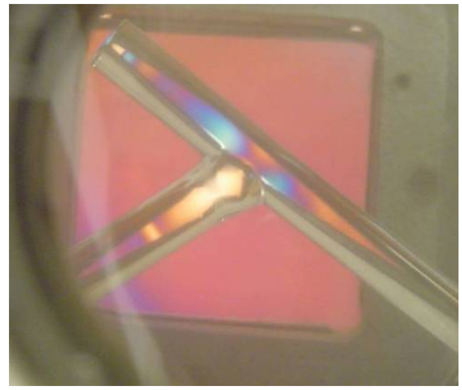
1 East Carolina University's Glassblowing services, Scientific glassblowing Basics, East Carolina. http://www.ecu.edu/glassblowing/gb.htm

2 Heller, P. Ververst, J. Wilbrink, H. (1992) Vademecum voor de glastechniek, Deventer. Kluwer Technische Boeken

Figure 3.10 Welded glass rods of 10mm

Figure 3.11 Stress distribution in the glass rods after welding, seen through a polarizer



3.3.6 Shapes

In principle glass bonds created with welding processes are tubular. Welding of flat glass is less common. This is because of the thermal properties of glass. The element that should be welded must be placed in an oven while welding. This is necessary to avoid failure because local heating can cause high temperature gradients[1]. It is possible to make joints between 0 and 90 degree angles and should be placed in the oven in that angle you want them to be welded.

Bending glass panes is also a possibility of making a variety of shapes. The flections do not have to have the same radius everywhere.

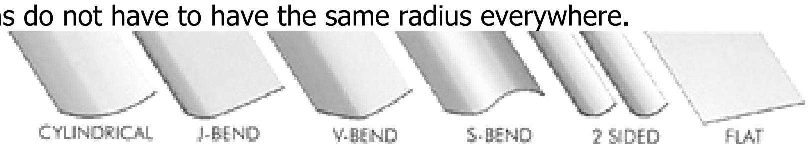


Figure 3.12 Bending options for flat glass

3.3.7 Welding techniques

Thermal deforming of glass is using the typical characteristics of glass. Glass is easy to deform in every shape when heating it up till the deforming temperature. The viscosity of the glass decreases and by means of bending, tearing and blowing it can be shaped into every form.

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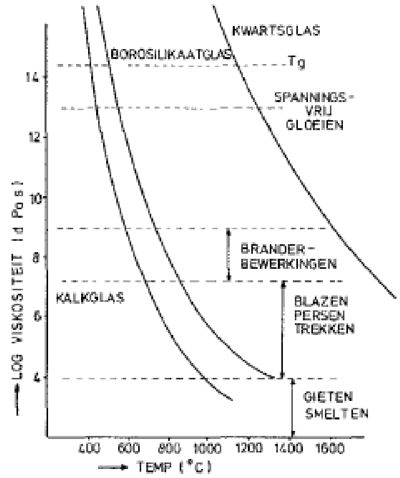
[1] Belis, J. Calleweart, D. Impe, R. van. Seamless connection of Soda lime Float Glass by Welding; Preliminary Test Results, Ghent.

Figure 3.13 Different processes at different temperatures

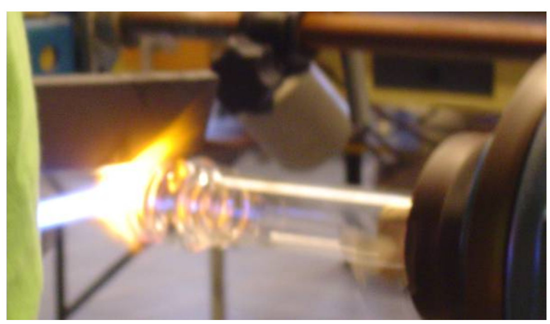


Glass welding is a technique which has been used in the development of laboratory ware. These elements usually are not that big and are welded and formed manually. Tube glass refinement has so far been largely performed manually using gas burners.

For the production of building size elements a lathe is needed. When joining two glass elements needs to be done under rotating movements, to distribute the heat equally. Working with fire takes many safety regulations. For the heating process it is necessary that the elements rotate on a fixed axis, so the torches can be set at a fixed position. For difficult forms an auxiliary construction is needed to keep the glass tubes in its position.

Graphite tools are used in the glassblowing industry as forming tools. Graphite withstands high temperature exposures and is easy to shape into many shapes. Graphite tools can be used to make tapers, flanges or decorations and enlarge blown holes.

Figure 3.14 Welding glass in a lathe. A graphite paddle is used to make shape the glass tube.



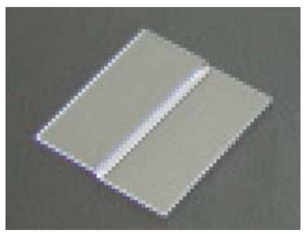
When flat glass is quickly cooled down at both sides by an airflow or oil bath, the surface will stiffen quickly and the centre cools down slowly. This will lead to compression stresses at the surface and tensile stresses in the centre. See also chapter 5 literature part. On the contrary cooling down tube glass, the outside will be cooled down first. This leads to compression stresses at the outside diameter and tensile stresses in the inside diameter. That is why tubular bonds should be cooled down in a flame. When this is not applied, stresses occur, and the glass product should be reheated to remove these stresses. The temperature gradient that is introduced by reheating leads to increased stress at the outside and inside diameter. These stresses may exceed the failure strength of glass and could lead to early failure.

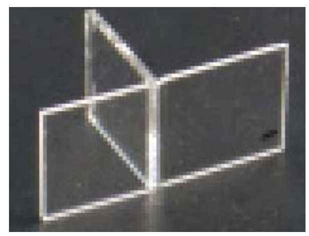
3.3.8 Developments in the glass welding techniques

All small products are formed manually with gas burners which lead to a variety in qualities. The CO_2 laser has been introduced to automate the manual work processes for the joining and forming of tube glass. This makes the process more efficient and the product quality improved.[1]
Local heating of glass objects with laser radiation will cause high temperature gradients by the low thermal conductivity. The thermal expansion induces stress that can exceed the materials strength, so that cracking could occur during the cooling down process. Therefore two means are applied to reduce the temperature gradients and the need to preheat the entire element. A band around the joint line will be heated, so that the temperature gradient decreases in the heated zone. Another strategy is using a multiple scan with high speed to evenly heat the material along the joint side.[2] With these methods it is possible to make welded joints in flat glass. Still it is only applied in very small size elements.

Figure 3.15
Butt joint 20mm

Figure 3.16
T-joint 10mm





[1] BNG Glass.(2007) European Glassblowers conference. http://www.bnglass.com/?page=gt_informatie&s=gt_3.2.3
[2] Center for Laser Technology, JOINING OF GLASS, Plymouth. www.clt.fraunhofer.com

H4. Introduction design process

The graduate department, Zappi, is a term for the search for the new and unknown. The name Zappi is created for the development of new extraordinary materials. Within this context a design for a new facade is made with the use of glass welding as a bounding technique. In this chapter the design process is written. It will give an explanation for the undertaken steps during the design process. This design project consists of an exploration to the opportunities of using glass welding as a construction method for designing a building component. The trusses in the street of the faculty of architecture of Delft University of Technology form the basis of this design project.

Figure 4.1 Space trusses of the faculty of architecture

4.2 Type of work

The architecture building was ready for handover in the summer of 1970. Van den Broek is the architect of the building. He wrote that the chosen architectural form may be described thus: a gradual transition from the general (public) context to the more specific (private) user space[1].

The faculty of architecture can qua composition simply be divided into a basement and a multi-story building. It is built out of concrete columns, beams, floors and a core in the centre of the multi-story building. The building's grid is 5,4 meter. The windows geometry is based on a multiple of the 5,4 meter grid.
Rectangular forms are repetitive, as well in the floor plan, the massiveness of the building and in the facade. The basement can be seen as 3 big massive blocks on which the multi-storey block is placed. The blocks on the ground floor are separated by a glass facade.
The entrance hall functions as a public square. It is a meeting place where people can sit, eat or discuss. Many visitors enter the building to proceed their

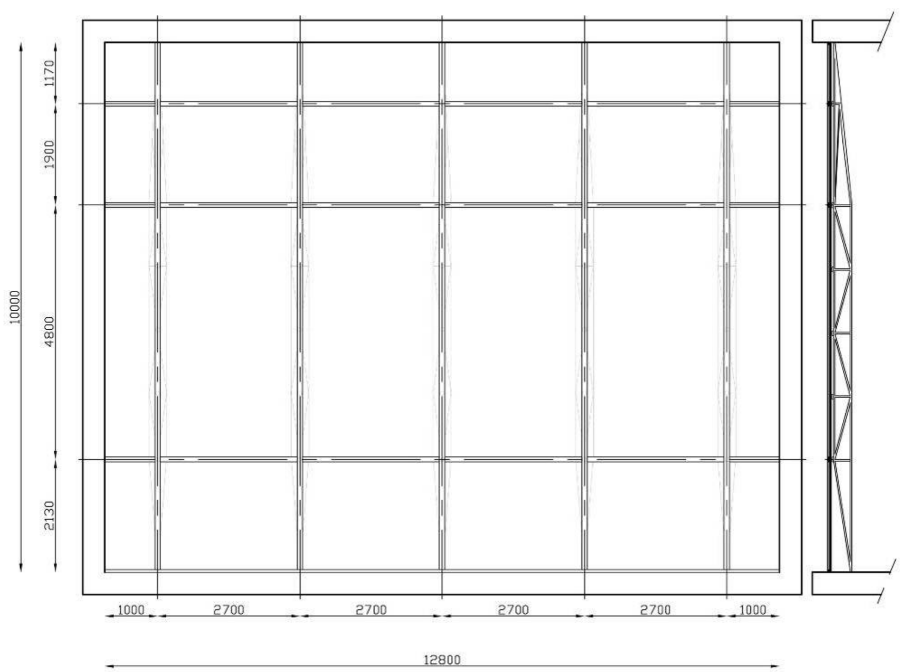
[1] Mácel, O. Schutten, I. Wegner J. Geschiedenis gebouw, http://www.bk.tudelft.nl/live/pagina.jsp?id=f33f5a10-c139-44f6-a9c1-151344b32ac6&lang=nl

way to other parts of the building. In this central hall the massive concrete blocks form a contrasting volume against the glass facade. The glass facade allow light to enter and give a view to the outside world. The trusses in front of the glass facade form a prominent construction. This type of wall can be described as a curtain wall. A curtain wall may be defined as a non-load bearing wall, where its own deadweight and wind load will be transported to the main building structure through anchorage points. A curtain wall also spans multiple floors.

4.3 Principle current situation

In the present situation the glass façade consists of steel space trusses and windows framed in steel profiles with wooden glazing bars. The glass facade in the entrance hall has a dimension of 12,8 by 10m. The 5,4 meter grid can be found in the horizontal direction of this facade, but in vertical direction the structure is adapted to the alongside facade. The structure the architect of the building used in the facade is presented hereunder and the supports of the present situation are presented in Figure 4.4 The heating installation, for the prevention of cold downdraught, in the floor has a width of 530mm.

Figure 4.2 Current glass facade structure of the faculty of architecture



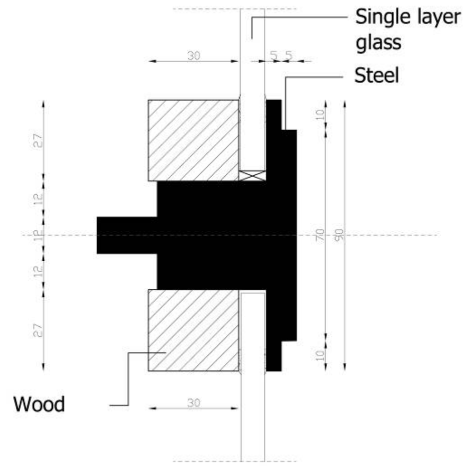


Figure 4.3 Steel window frame with wooden glazing bars

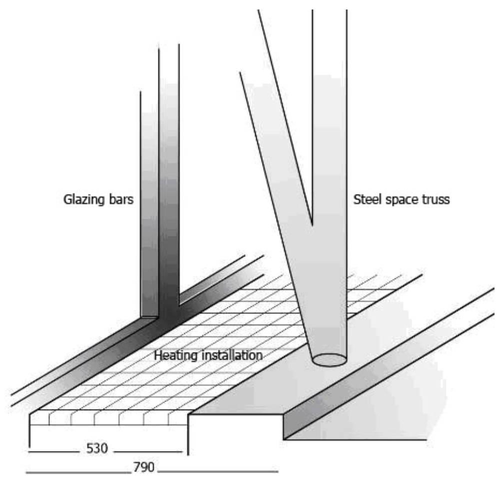


Figure 4.4 Support of the truss and heating installation in the floor

4.3.2 Working principle current situation

A facade is subjected to wind loads, Q_w, and it own weight. Wind causes pressure and suction on building facades. In Figure 4.5 the moments and shear forces caused by the wind load are illustrated.

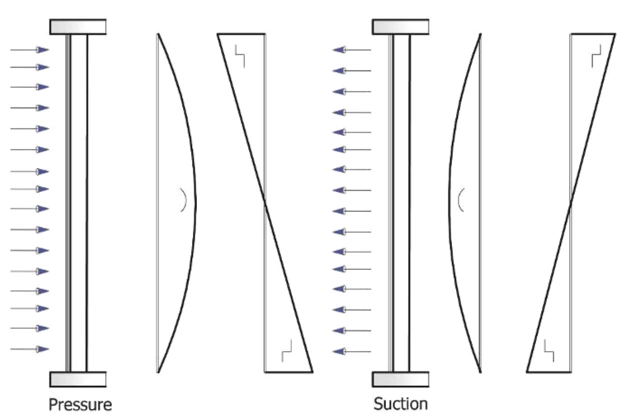
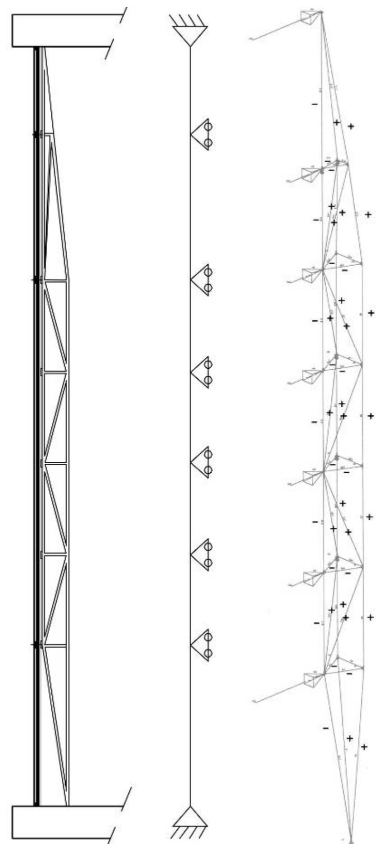


Figure 4.5 Bending moment and shear force diagram caused by an uniformly distributed load

The wind load, Q_w, will uniformly be distributed over the glass façade and be transferred to the space truss behind the glass façade. The truss has the task to avoid the steel window frame from buckling and the steel window frame carries the deadweight of the glass panels.

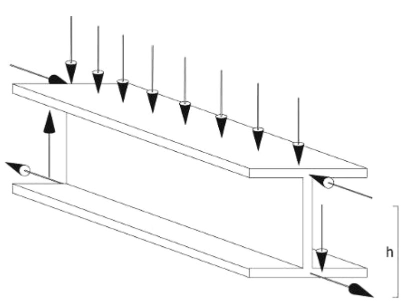
Figure 4.6
Working principle current situation

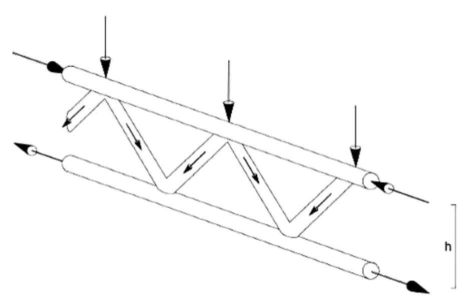


The basic principle of designing a truss is based on the working principle of a beam. The "extra" material at the top and bottom of a beam, the flanges, has the task to give resistance to the bending moment. The body has to transfer the shear forces. A moment is a force multiplied by the distance. The higher the beam gets the higher the moment it can resist. A truss is an efficient way of accommodating bending moments. The forces preferably seize on a node to prevent bending moments in the top beam. This construction is designed so that only normal stress occurs.

Figure 4.7
Beam

Figure 4.8
Truss





4.4 Goal definition

For the glass façade described in the last paragraph a new space truss will be developed. Glass will be used as a structural material to develop a new truss. Within the scope of Zappi, the ultimate goal is to create a strong, stiff and tough material that is transparent and would not fail abrupt. To explore the possibilities within using glass as a construction material, glass welding might offer an opportunity for geometrical freedom. This is the reason that glass welding is the main subject in designing the truss. Glass welding will be used to joint the different glass parts. The process of component development can be divided in three groups[1]:

- Standard building products
- Building system or sub-systems
- Special building component

The initiative to use welded glass in the building industry has a innovative foundation. Glass welding has not been used up until now in the building industry. The main reason to construct with glass is because of its transparency. It is there, but at the same time it is not there. It reflects and refracts light when looking at it from a specific corner. Because this component involve a product designed for on specific project is encompass a special building component.

4.5 Starting points

4.5.1 Technical constructive starting points

The starting point for the design is the trusses in the Street of the faculty of architecture.

The design will consist of borosilicate glass. This type of glass is usually used for welding processes. It has a low coefficient of thermal expansion and is therefore easy to weld. This is further explained in chapter 3 literature part. The preliminary design will be constructed out of glass tubes, because of the greater possibilities. The glass welding industry is mostly focussed on tubular structures. The facilities are attuned to these forms. The tubular form is easier to heat and weld in a lathe. Besides more form freedom is possible. It is not common to weld flat glass, because of the difficulties that appear when thermal stresses can not flow out.

Using glass is usually for its transparency. The possibilities of using glass should be explored and to keep the high level of transparency, the mass of the component should be reasonable.

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[1] Jong, T.M. de, Voordt, D.J.M. van der. (2002) Ways to study and research, urban, architectural and technical design, Delft, DUP Science

Figure 4.9
Ground floor of the faculty of architecture

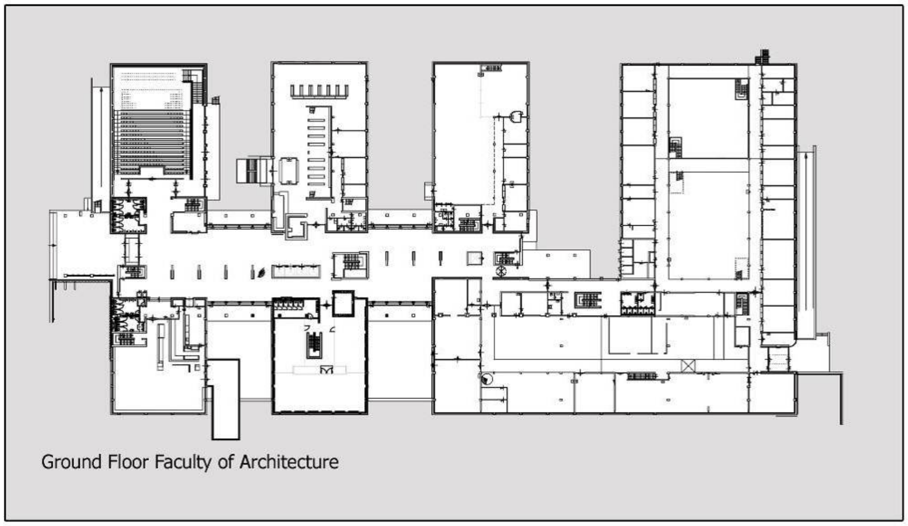
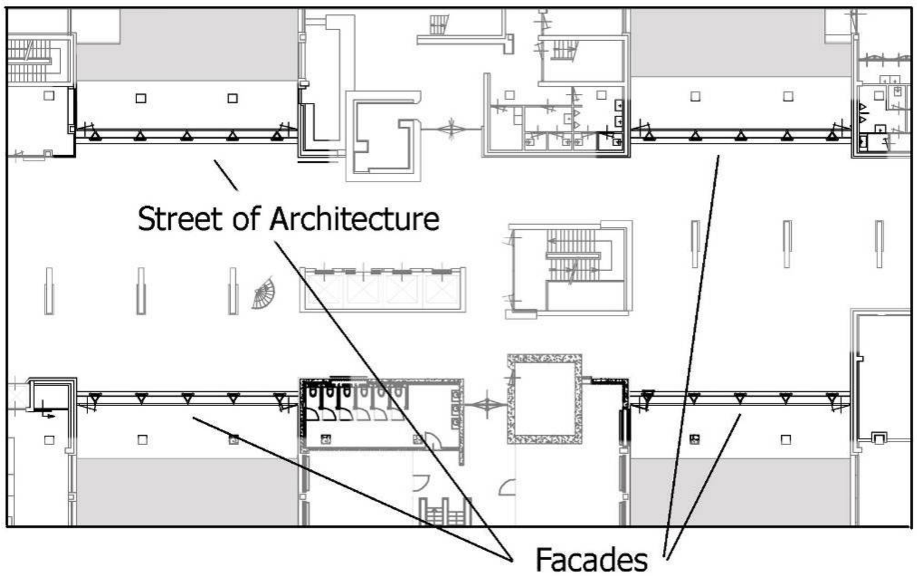


Figure 4.10
Street of architecture and the glass facades of the design project



4.5.2 Social starting point

When using constructive glass the users of the building should feel save. The truss is a prominent and visible structure in the hall of architecture.

4.5.3 Economical starting point

The costs will be omitted in this research.

4.6 Requirements

4.6.1 Functional requirements

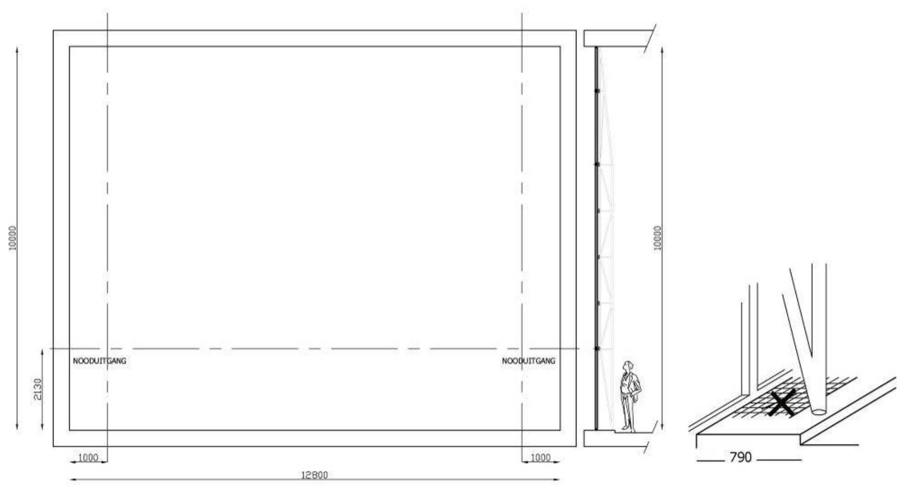
On the ground floor level the structure may not hinder the view to the outside and the major road through the street of the faculty.

The emergency exits should be maintained in the new situation. These exits exists in both corners of the glass facade.

The current heating installation in front of the facade will be omitted. The current facade has a single glass layer with a low insulating value. To prevent cold downdraft the heating installation is placed under the large glass facade. With the design of a new facade principle an increased insulating value will be applied so that the heating installation wouldn't directly be necessary anymore. The support of the truss may be placed within the 790mm from the facade.

The total construction of the facade will span 10m in height and 12.8m in length.

Figure 4.11 Design restrictions



4.6.2 Technical requirements

Strength
A construction is accommodated to loads. A construction must be stable and strong enough to transfer the loads to the foundation. The design strength is determined with the help of testing specimens. This is further described in H11 and further experimental research.

Transfer of loads
The construction will be controlled on strength at wind pressure, strength at wind suction and the deflection at wind pressure. Glass is weak in accommodating tensile forces, but strong in accommodating compression forces. For this reason the construction will designed in that way, that the glass construction is mostly loaded on pressure. The representative loads are calculated in paragraph 8.2 .

Deflection
The deflection of a wall may not be noticeable. The public might concern that the wall is not strong enough.

Safety
The construction has to offer a certain safety.

4.6.3 Execution requirements

Manufacturability
Especially with the introduction of glass welding in de building industry, the making process is important to take into account. Standard available glass profiles will be used for the design. Next to that the welded glass parts have to be made with the current production processes.

Transport
Transporting construction materials is limited to certain sizes and during transport also dynamic loads exert. The construction must be transportable in size and accommodate these dynamic loads.

4.7 Reference projects

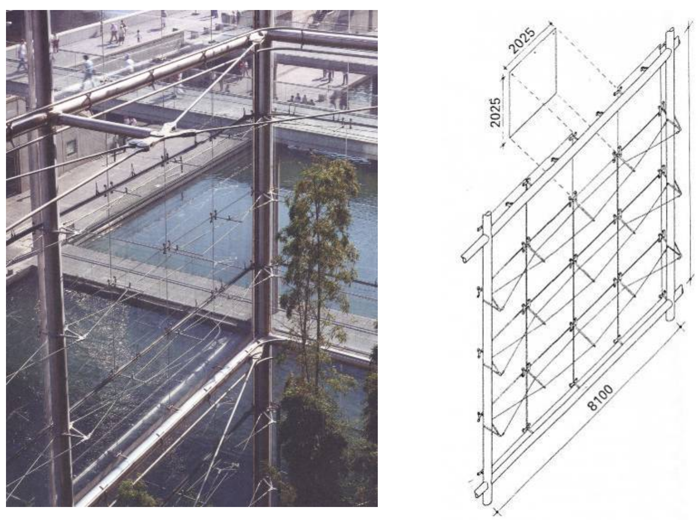
From the requirements and starting points, some reference projects are attended.

4.7.1 Cité des Science et de l'industrie

Parc de la Villette Paris 1986
Architect: Adrien Fainsiber
Engineer: Rice, Francis and Ritchie

The glass structure of the exhibition building of Parc de la Villette consist of 2x2meter panels, 12mm toughened glass, forming a 8x8m glass facade. The glass facade is hung from the top by the means of a spring connection. The other panels are all, one below another, suspended from these. Point fixings with articulated fixings are used to reduce the concentration of high bending and torsion forces around the drill hole. This hanging glass facade is stabilized against wind load by horizontal cable construction.[1]

Figure 4.12
Cité des science et de l'industrie



4.7.2 Glass Tube Field

Tower Place, London 1998 – 2003
Building architect: Sir Norman Foster & Partners
Engineer: Arup Facade Engineering

This project is designed as a public space between to new buildings. The facade structure is a suspended curtain wall. A glass prop supports the glass planes and a post tensioned stainless steel rod is running trough the centre of the glass tube. This gives an illusion that the wall is unsupported. James Carpenter, Luke Lowings and Richard Kress developed the concept design and feasibility studies for the visual and structural concept.[2]

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[1] The institution of Structural Engineers Structural (1999), Use of glass in Buildings, London. SETO
[2] Marpillero, S. (2006) James Carpenter, Environmental Refractions, Basel. Birckhäuser.

Figure 4.13
Tower place structure

Figure 4.14
Detail connection glass tube

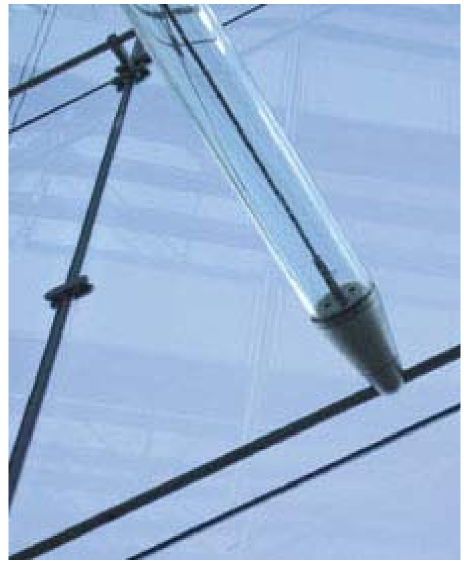
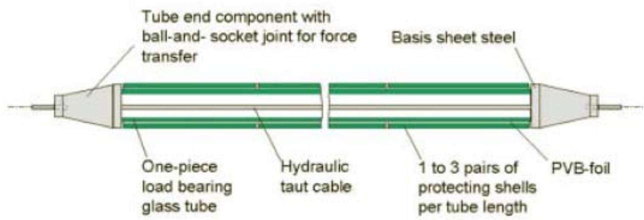


Figure 4.15
Laminated glass tube of the tower place

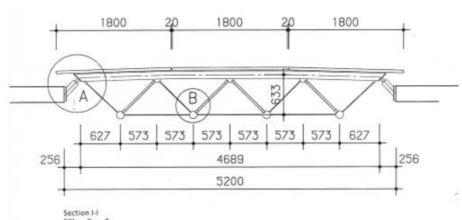


4.7.3 Glass truss elements

Buidling office, Amstelveen
Engineer: Rob Nijse

The roof structure of the restaurant has a glass column concept.
The W-shapes truss consists of steel and glass elements. The compression loaded parts of the truss are made of massive borosilicate glass bars of 30mm in diameter. The steel cables are 10mm thick.[1]

Figure 4.16
Glass truss



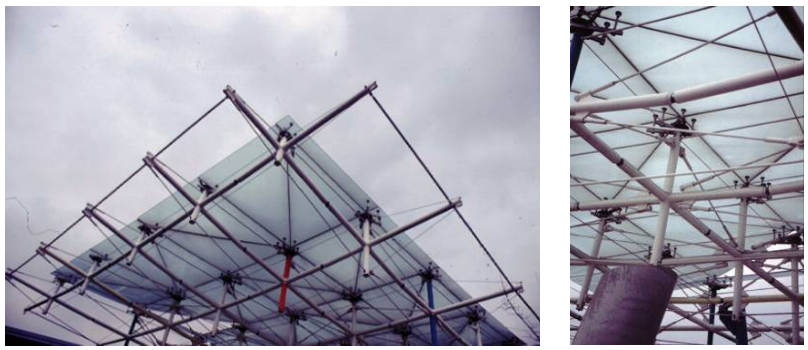
[1] Nijse, R.(2003) Glass in Structures, Basel. Birkhäuser

4.7.4 *Glass sky*

Building architect: Kauffmann Theilig, Stuttgart
Engineer: D. Weischede, Glasbau Seele

This glass sky form an underpass for the IGA in Stuttgart. A modular system is created to create a slightly curved roof. Because the truss is built out of bullets, bracings and star-shaped truss elements, it can take many forms. The truss elements are connected by tie bars. These tie bars tighten the system and form a grid construction. The star-shaped compression elements are made out of tubular steel profiles. The bracing is connected to with the help of clamps and anchor welds. [1]

Figure 4.17
Glass sky

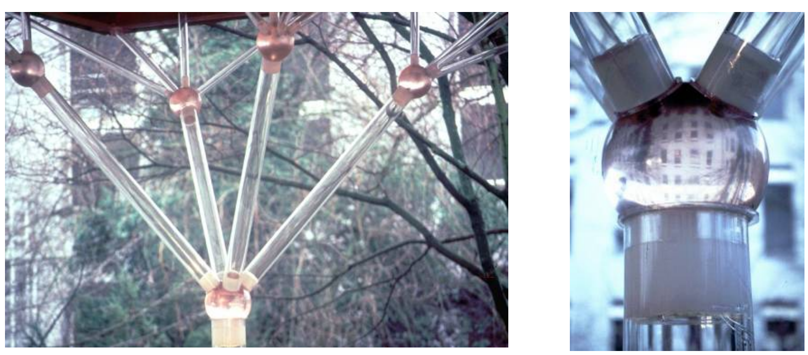


4.7.5 *Glasbaum*

Aachen 1998

The concept of this experiment is using glass tubes as compression elements. For this a three is designed, where the geometry has an optimal force distribution. The loads from the roof are transported as compression forces to the glass tubes and the ball joint united. The ball joints are made out of epoxy and steel bolts.[1]

Figure 4.18
Glasbaum



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[1] Knaack, U. (1998) Konstructiver Glasbau, Hannover. Schlütersche Druckerei

H5. Restrictions to glass welding

5.1 Limitations glass welding

Glass welding is used for small laboratory ware. Therefore it is necessary to know what the boundaries are in manufacturability. I visited Louwers, a company of glass and ceramic technologies in Hapert on December 16th 2006.

Louwers glass and ceramic technologies is specialised in the development and production of technical glass and other ceramic components.
I had an appointment with Mr. Schepens to talk about all the possibilities of glass forming. Actually everything is possible qua form, but the logical consequence is the more difficult the forms are the more effort for making it. They could make the smallest elements out of technical glass for the bio industry, sensors, lightning and medical applications. So they are very specialised in miniature precisions, but they also make large sized products with great precision. However the large size products are limited to certain sizes. The dimensions of the machines and the annealing furnaces are the obstacle to produce larger sizes.

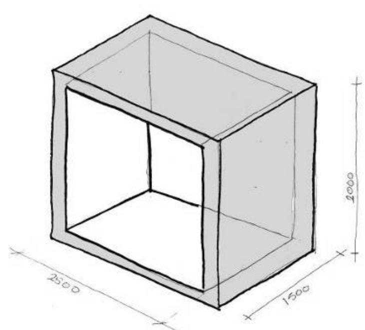


Figure 5.1 Maximum size annealing oven

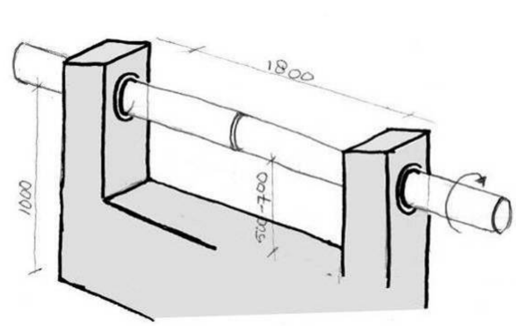


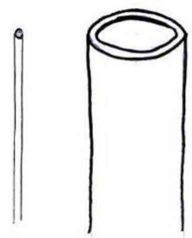
Figure 5.2 Maximum size welding lathe

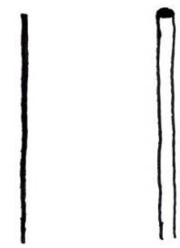
Welding of flat glass is also done at Louwers, but usually the sizes aren't bigger than 400mm and they work with a thickness of 3.3 mm. Mr. Schepens expected that thicknesses till 10mm might be possible.

The provider is Schott glass in Germany and the glasses Louwers work with are DURAN and BOROFLOAT.

The borosilicate glass type that is used for the most general-purpose glass is 8330 (DURAN). This glass type is available as block glass, capillaries, moulded glasses, pressed or blown, rods, glass sheets and tubes. The standard length is 1500mm and the standard available sizes are listed in table 5.1.

Figure 5.3 Tubes
Figure 5.4 Rods
Figure 5.5 Glass panes





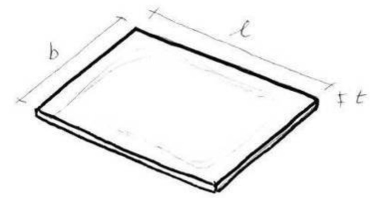


Table 5.1 Size limitations

Min		Max	
	0.10		5.0
3.0 x	0.15	325x	7.0
	0.20		9.0

Min	Max
3.0	30

l	b	t
1150	850	0.7-25.4
1700	1300	16.0-21.0
2300	1700	3.3-15.0

Note: The deliverable sizes of borofloat to Louwers are squares of ~800x800mm

Strengthening flat glass is no problem. This can easily be done in a furnace. Strengthening of glass tubes is a possibility, but this is not a simple process. These pre-stressed tubes are called DURATAN. After welding and forming, they could give the glass product an oil bath for strengthening it. Only this is very difficult, already for little complicated forms.

Figure 5.6 Stress distribution in a strengthened glass tube

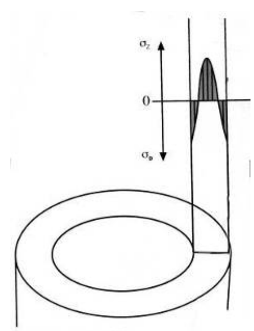


Figure 5.7 Stress distribution a different diameters

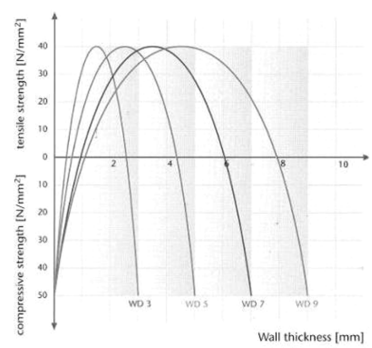


Figure 5.8 Availability DURATAN

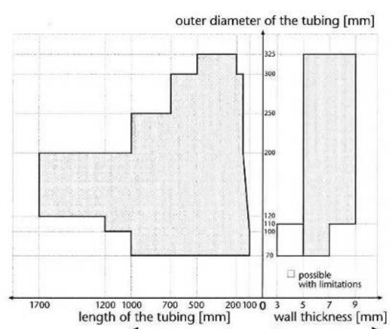
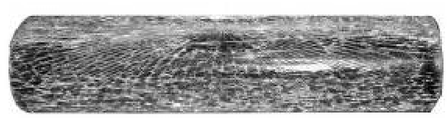


Figure 5.9 Broken DURATAN glass tube



Borosilicate glass only deforms at temperatures which approach its transformation temperature (approximately 525 ºC) and up to this point it retains its mechanical strength[1].

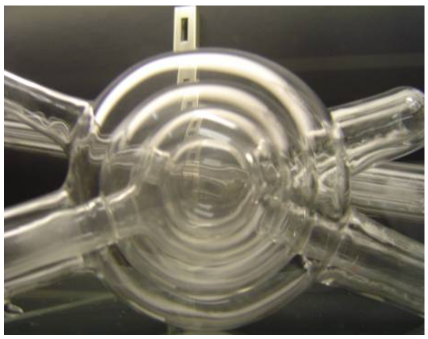
[1] QVF process systems, Mainz http://www.qvf.com/en/Equipment_1/Borosilicate%20glass/index.shtml

5.2 Welding geometries

The exploration of glass welding possibilities is related to detailing. Glass welding principles can be found when looking at laboratory ware. Many small glass tubes are formed and welded together. It creates magnificent forms. To create a joint with the glass welding process leaves us to a construction where two glass tubes meet. These recognizable joints can be found in many objects even when looking at welded steel the typical geometry is distinguishable. By melting two materials a stiff connection is made. A stiff connection means that two parts can not translate or rotate in relation to each other.

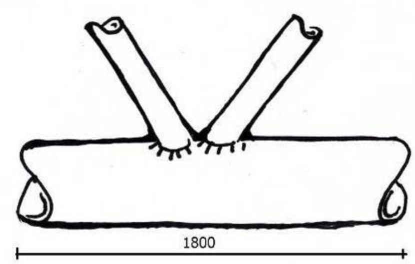
Figure 5.10 Welded glass

Figure 5.11 Typical welded joint (in steel)



The preliminary design will be constructed out of glass tubes with a maximum size of 1800m length, because of the possibilities within the glass welding industry. For the exploration of glass welding applications the geometry of the weld of the truss will be build out of this type of joint, with the characteristic properties of a stiff joint.

Figure 5.12 Principle joint for glass welding



5.3 Form study according to welding

Small objects for the production of laboratory ware can be made manually. For the production of building size elements a lathe is needed. Due to these limited production methods, the façade truss will be build-out of elements. Each element has a maximum size of 1,8 meter.
When joining two glass elements needs to be done under rotating movements, to distribute the heat equally. Working with fire takes many safety regulations. For the heating process it is necessary that the elements rotate on a fixed axis, so the torches can be set at a fixed position. The glass tubes form the starting point for other geometries.
Standard available glass profiles are tubes, t-joint, y-joints and U-profiles. With the help of these form new geometries can be made, as long as the axis of both elements coincide and rotate on a fixed axis.

Figure 5.13
Standard welded geometries in a lathe

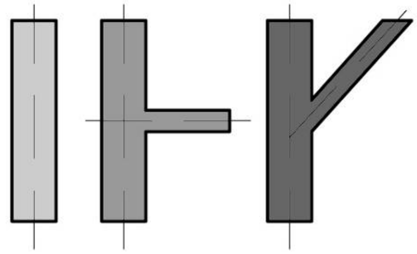
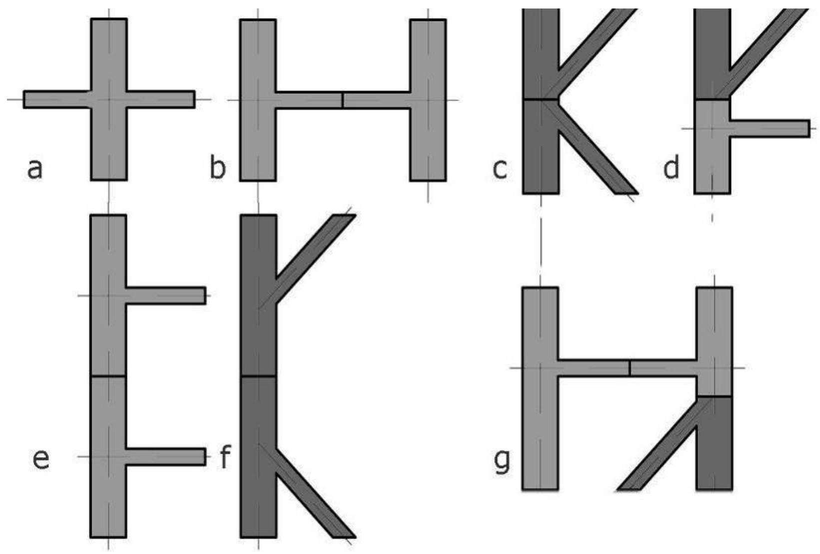


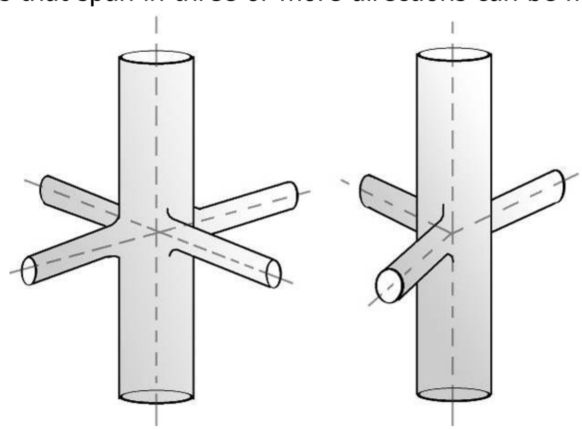
Figure 5.14
Combining elements 2d



The elements in Figure 5.15 can be made with a lathe. The accuracy of the parallelism of each element need to be examined. According to Mr. Schepens from Louwers glass and ceramic technologies, all elements are made with very precise techniques. For the production of the elements can be assumed that the dimension tolerance is small.

Also elements that span in three or more directions can be made.

Figure 5.15
3d elements



H6. Geometry definition

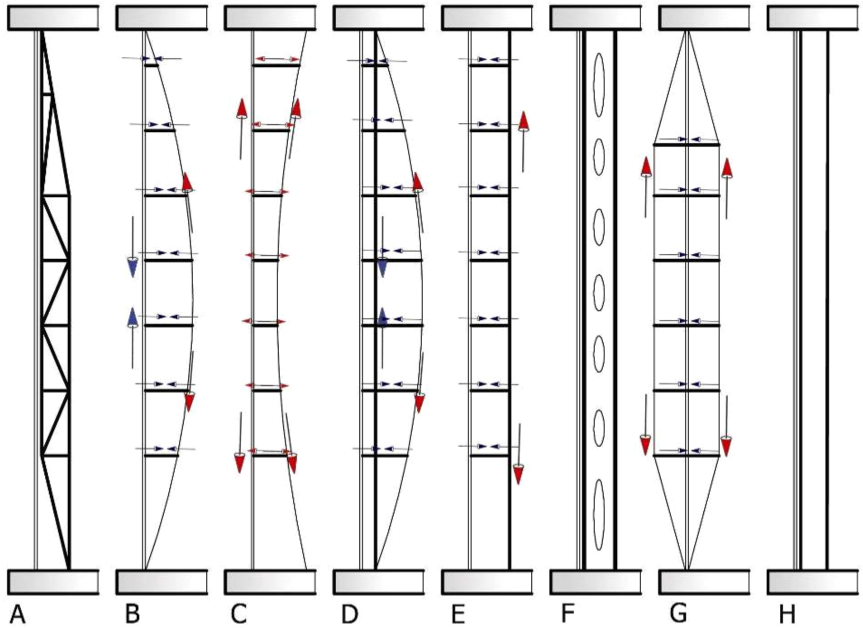
6.1 Introduction

Glass is weak to tensile; this means that the construction should mainly be loaded on compression. But the biggest problem of a wind truss is that it works in two opposite ways. It works inverse under pressure and under suction. The pressure from wind load is 55% higher than suction. (see paragraph 8.2) The trend at this moment is to create a highly transparent glass facade. With the help of cables and pre-stressing components, the transparency had increased in the last decennia. There are a few basic principles used as facade trusses. These principles are outlined hereunder. Variations on these principles are possible.

6.2 Facade truss geometries

Design A	The construction in present situation. A spatial truss made of tubes to avoid the steel window frame from buckling. The truss is only subjected to normal forces, because the flanges are coupled by tensile and compression elements. The structure is completely welded.
Design B	A construction like a subtended beam, a tensed wire construction. The beam in this design is the glass façade. The glass façade is integrated with the background construction. At wind pressure the glass façade will be under pressure and there are compression rods in between the glass façade and the tie bar.
Design C	This construction is comparable to B, but the entire construction is under pre-tensile stress. The glass façade and rods are under tension as well as the tie bar.
Design D	The glass façade detached from the truss. The truss works as a subtended beam. The glass façade has to carry its own weight and does not interact with the background construction. The middle column is a compression element. It is a combination of design A and design B.
Design E	A stiff framework behind the façade. This performs as a increased size of the glass facade, like a beam behind the facade. The coupling of the truss is done through bending elements. The bending moment will be quite high in the joints.
Design F	A variant on the castellated beam. Material is removed on the places where it is not directly necessary to accommodate the shear stresses. Coupling of the flanges are done by plate elements.
Design G	In this construction the façade is clamped between compression rods.
Design H	A (glass) fin of flat glass is suspended from its top support. The area of the fin will accommodate all forces.

Figure 6.1 Truss principles under wind pressure



6.3 Choice accounting

From the truss principles that are described in paragraph 6.2, a basis principle is chosen for further design.

According to the limitations of glass welding, the geometry of the truss will be built out of glass tubes. This eliminates principle F and H directly.

Principle A is a challenge when welding techniques are used. The current situation is made out of steel and steel can be welded during the phase of construction or in the factory. The construction will be 10 meters high and can be moved on a truck. Steel can easily accommodate dynamic forces. Glass is in comparison to this very weak. It is not (yet) possible to weld glass on the building site, therefore this geometry will be a huge challenge to realize. The limitations of the lathe makes it not possible to make these geometries. Manually there might be options for making this geometry, but the size of the truss is to big to manufacture manually.

Principle B, C and G are built out of compression rods and steel cables. The compression rods are only interesting in using the glass welding technique when these exceed the 1500mm in length. This is the maximum fabrication length of the tubes. To elongate these butt joints can be made. This geometry is very limited in form and to explore the possibilities of free form glass, these principles won't be a challenge for this graduation project. This principle is already used in the Tower place in London and a concept is made for the faculty of Architecture Delft by ir. Freek Bos[1].

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[1] F.P. Bos, F.A. Veer, (2007). Bending and buckling strength of borocilicate glass tubes, Delft.

This leaves us principle D an E. Principle E can also be eliminated immediately. This principle will lead to tensile stress is the main column. As earlier explained, glass is weak in accommodating tensile stresses.
Principle D is a good basis for the design. It has the type of joint that can be welded and forms a good basis for the force transmission.

6.4 Design Variant 1. Principle D

A glass façade is subjected to wind loads. Wind is very unpredictable and differs is strength and direction. As described earlier wind can cause pressure, but also suction on a façade. This means that the posterior construction should work in bidirectional.

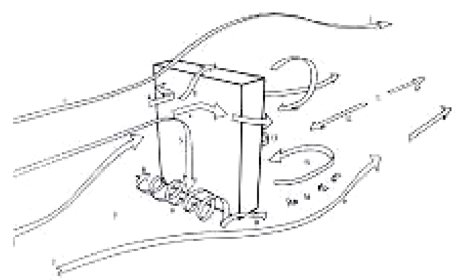


Figure 6.2 Behaviour of wind around a building

In many glass facades tension cables are applied to withstand the wind load. The lightly curved shape of the tension rods create a uniform pressure on the compression tube and pre-stresses the façade construction op de truss. When looking back at principle D, the conclusion can be draw that the structure won't work in opposite direction. The moment that is generated by the wind load has to be accommodated by the structure. A moment is defined by force times arm. The arm, a, is very short, which results in high tensile forces in the framing of the window and high compression forces in the vertical member of the glass truss. This means that the moments had to be accommodated by a small construction height. The displacement of the vertical member so that a symmetrical structure is generated, results in a proportional stress distribution.

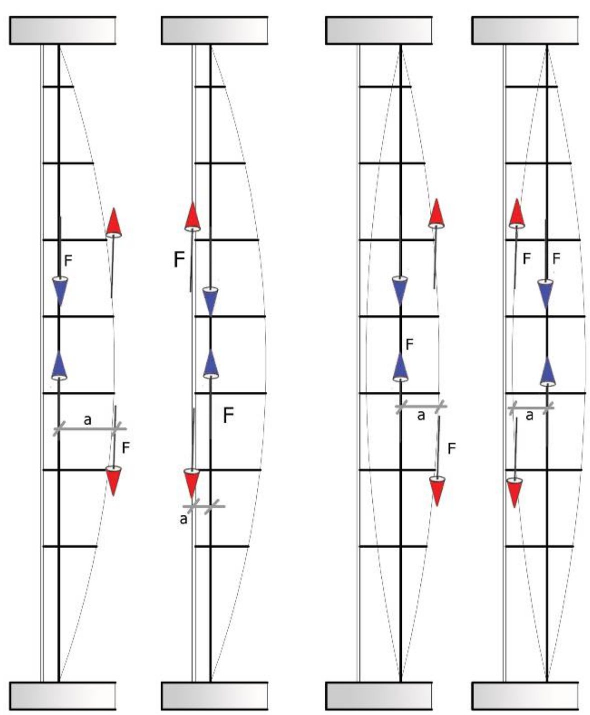
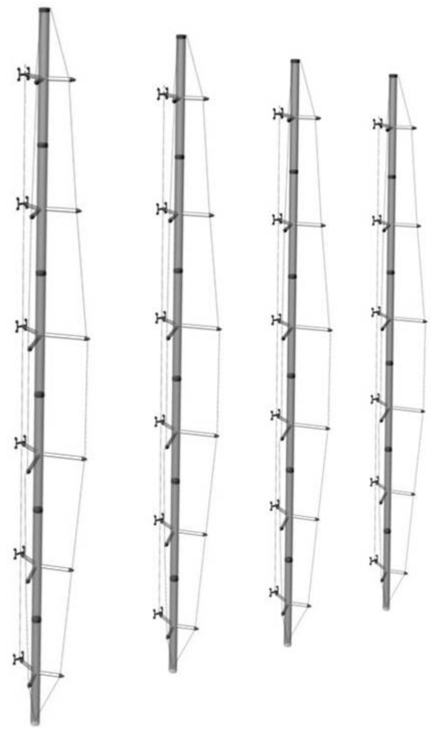


Figure 6.3 Effect of positioning the compression tube

6.5 Design Variant 2. "The Spine"

This design is derived from the vertebra and consists of elements of 1.8m, with three arms. See also Figure 5.15

Figure 6.4 Spine construction



In nature everything is based on minimum use of energy. The background of this process can be found in the cellular basis. Mammals have muscles and tendons to distribute the tension and are helped by compression absorbing bones. A triangle shape has a high mechanical strength and stability using the minimum of energy.

Design principle D is a slender construction. The stability of a very slender construction is worse than a construction with a larger basis. The moment of inertia is in the x and y-direction much higher than a single. The higher the moment of inertia of a cross-section the better the construction can resist deflection. Tilt over of a beam is usually the problem of beams with a relatively high torsion stiffness in the strongest axis and a relatively low torsion stiffness in the weakest axis. Tilt over can be avoided by adding outriggers.

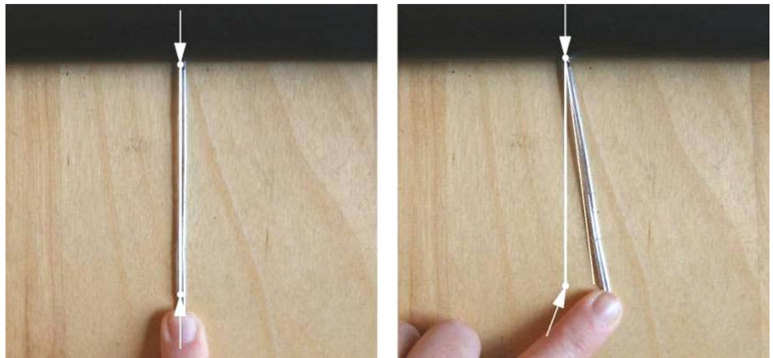


Figure 6.5 Stability of a slender construction

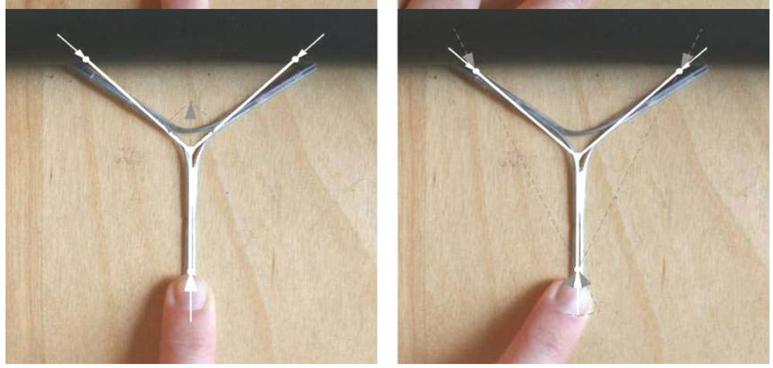


Figure 6.6 Stability of a construction with a wide basis

The bones in human's body are bonded like cable-stayed structures. The basis of this idea is derived from the vertebral column. The vertebra has a vertical member and 2 or 3 condoyle, dependent on cervical, thoracic or lateral part of the spine. The vertebras are placed one above each other and connected by the facet joints. A spine is very motile.

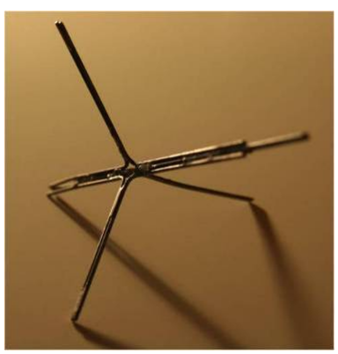


Figure 6.7 Element for building-up the facade truss

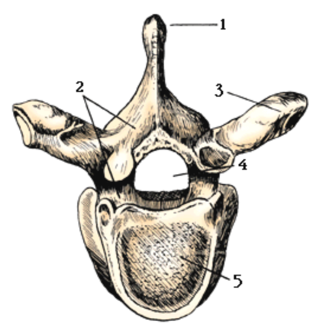


Figure 6.8 Vertebra

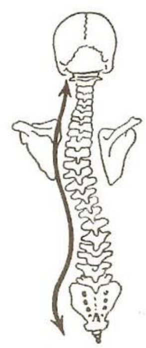
The spine is surrounded by many muscles and ligaments to give it strength and stability. Muscles are different than cables in a construction. Muscles are self-regulating cables. The regulation of the muscles is coordinated on neurological levels. If one side of the body's muscles is stronger or is not symmetrically build-up, like one longer leg, deformation of the spine originates.

Figure 6.9
Spine construction façade truss

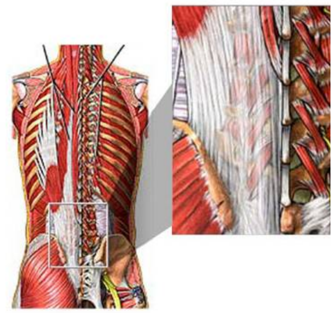
Spine construction

Figure 6.10
Structure of the human's back

Normal Spine



Scoliose



Muscles Back

In a construction the pre-stressed cables must be symmetrically distributed. This spine construction is build out of separate elements, like the spine itself. To avoid rotation of the separate elements, the joints should be designed to solve this rotation.

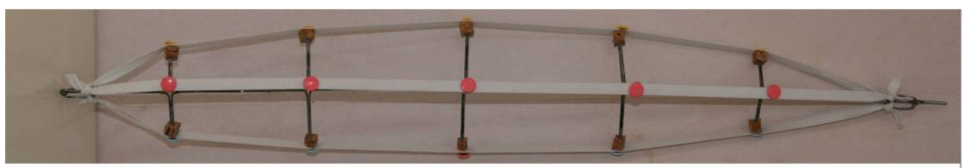


Figure 6.11
Model of the spine

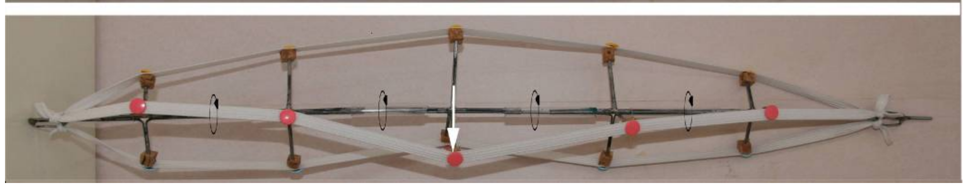
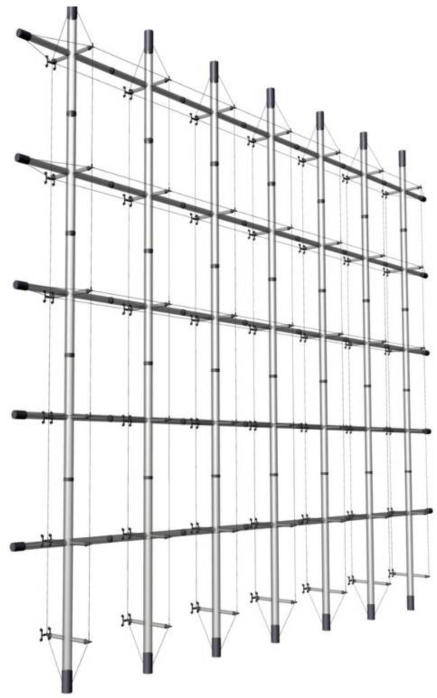


Figure 6.12
Torsion of the elements

6.6 Design variant 3. "The square net"

This variant is based on element of 1.8 meters with 4 arms perpendicular to each other. This results in star-shaped glass elements that can be piled up and next to each other and form a net-structure.

Figure 6.13 Square net variant



Designing within the building technology has to deal with mechanics, but also with aesthetical aspects. The faculty of architecture is made out of rectangular forms through out the building. From the aesthetic point of view can be concluded that the spine does not fit the rectangular geometries of the building. When looking at the two pictures hereunder, the second design creates a tranquil view and seems to correspond with the surroundings.

Figure 6.14 Design based on the spine structure

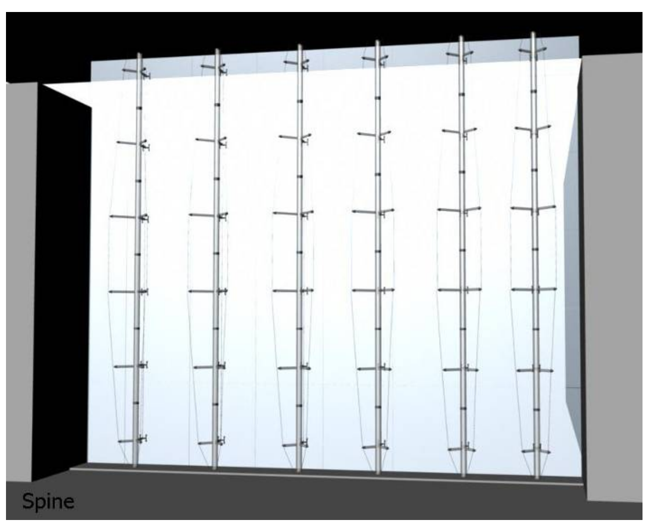
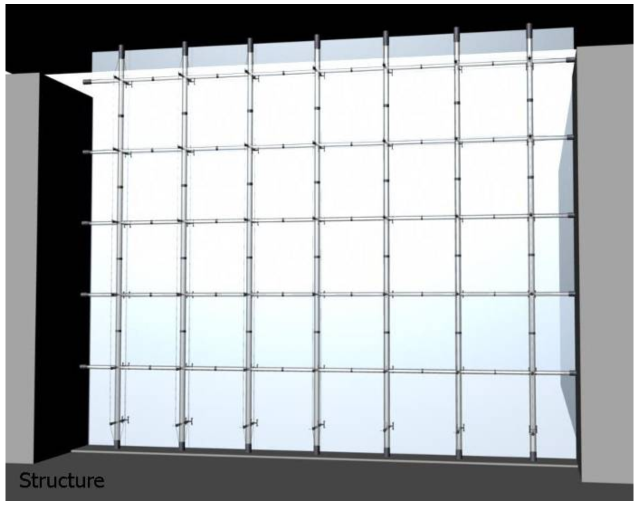
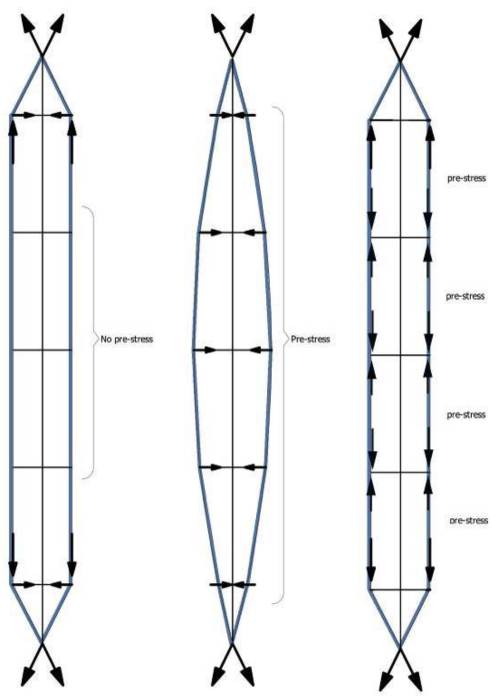


Figure 6.15
Design based on star-shaped elements



From the mechanical perspective is "the spine" variant more efficient qua form. By tensioning the tension cables, pre-stress can be introduced in the construction. With this it is possible to reduce the tensile forces in the construction. By the curved shape of the tension cables the forces are distributed evenly. When tensioning the cables in "the square net" construction, high compression forces occur in the top horizontal carrier. This would not lead to uniformly distribution of the construction. This means that the cable should be cut in separate parts and each part must be tensioned. According to the mechanics the spine has a better form. It follows the bending moment diagram. In the middle of the construction occurs the highest moment and at that point you have the largest construction height. This leads to higher material efficiency. Pre-stressing the spine construction is much easier because of its form.

Figure 6.16
Pre stressing of the square net and the spine variant



However the advantage of a square net is the bidirectional force distribution. If one element fails the construction will work together due to the horizontal coupling. This results in a smaller part of the loads has to be passed to the remaining structure. The spine variant has transfer the load over the complete height, has to be accommodated by the two alongside columns. In the square net variant a certain safety is guaranteed.

Figure 6.17 Collaboration of the elements after failure

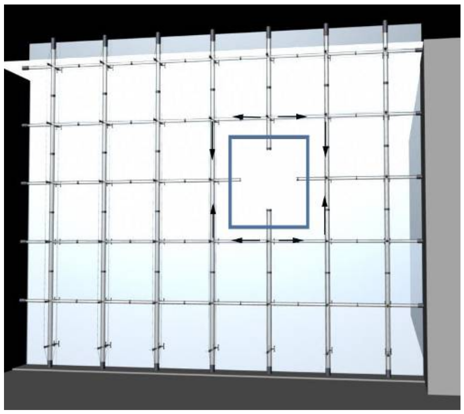
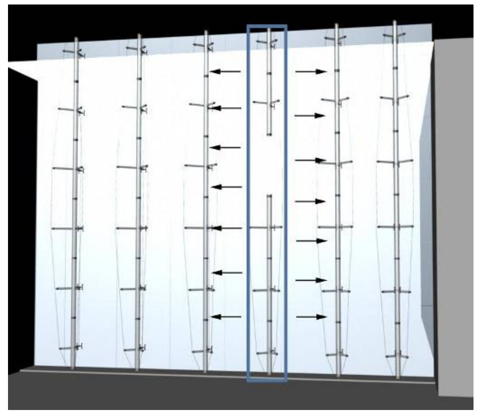


Figure 6.18 Force distribution when one element fails

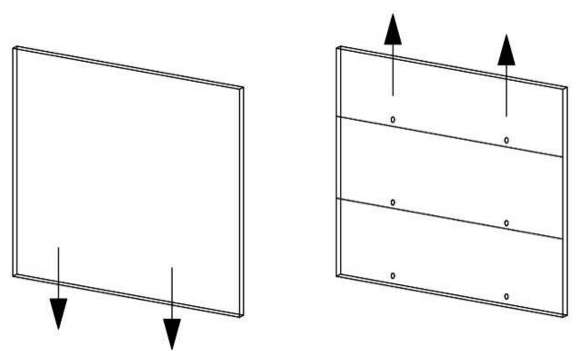


H7. Geometry Facade structure

7.1 Glass facade

The glass façade in this research can be defined as a curtain wall. Possibilities of assembling the façade to the main construction can be done on a standing or hanging manner. Suspended glazing makes it possible to create great glass surfaces, by using the gravity to remain all glass panes in position. The glass panes are hanged at the top, so that buckling is prevented and thinner glass panes can be used. Because the glass surface in this project has a dimension of 12.8m width and 10m high, the suspended façade is applicable. A suspended system should allow vertical movements and must be free to move at the bottom. A suspended façade can be designed in such a way that if one pane fails, not all panes drop, but stayed hanged on its support. Suspended glazing is among others applied at Famer Dumas and Park the la Vilette.

Figure 7.1 Principle of a standing and suspended facade



7.2 Facade Structure

The current situation of the facade has a centre to centre distance of 2,7meters. This makes the facade quite open and big glass panes are used. The maximum size of 1,8 meter per element gives the opportunity to work with a grid of 1,8 meters and smaller. When reducing the grid size, the façade structure will increase in massiveness and becomes a rag construction. Continuity in the structure is necessary to create a calm image. Using the 1,8m grid also adapts to the building design, where 5.4m is the planning grid on which the building is based. The arms of the first glass element start above the 2.10 meter. View to the outside will not be disturbed and that people do not bump their head when using the emergencies exits.

Figure 7.2
Glass façade
grid 1.8x1.8m

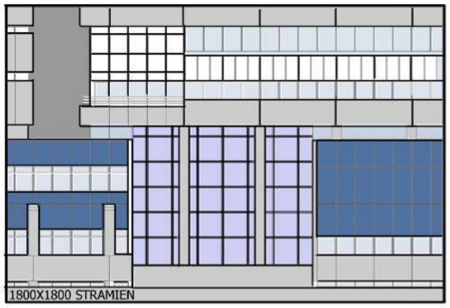


Figure 7.3
Glass façade
grid 1.4x1.4 m

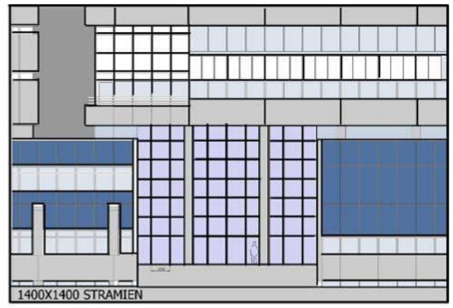


Figure 7.4
Glass façade
grid 1.08x1.08m

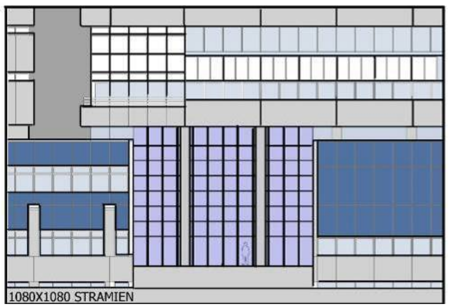
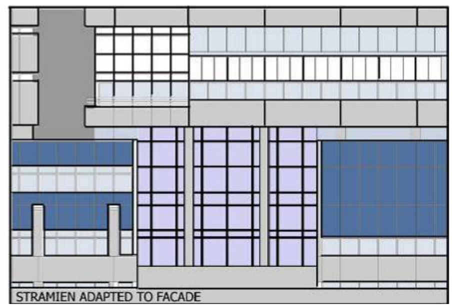


Figure 7.5
Glass façade
grid adapted to
the alongside
facade.



7.3 Element geometry

The element geometry of the glass space truss can be divided into two possibilities. All glass tubes converse in one point (element A) or each glass tube has its own direction and position according to the main column (element B).

Figure 7.6
Element A

Figure 7.7
Element B

The stresses in the joint are much higher when all 3 tubes interfere. Due to material absence for the gradual transformation of the forces, high stresses occur at the welded. To give an indication about the stress distribution in the joint a calculation is made. With the help of the finite element method in DIANA, glass tubes are modelled. The elements have a size of 0.7x1.8x1.8m, with a glass tube of 40mm diameter and 3.2mm thickness in x-direction, in y-direction a glass tube of 60mm and 5mm thickness and the main tube in z-direction of 80mm and a thickness of 5mm. From these calculations can be seen the stresses are 3 times higher when all tubes meet in one point.

Figure 7.8
Element A
S1 max
74N/mm²
S3 min
118N/mm²

Figure 7.9
Element B
S1 max
26N/mm²
S3 min
33N/mm²

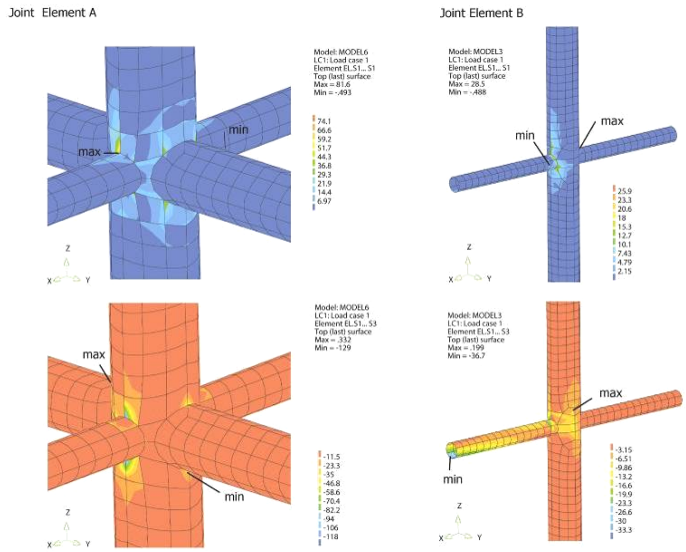
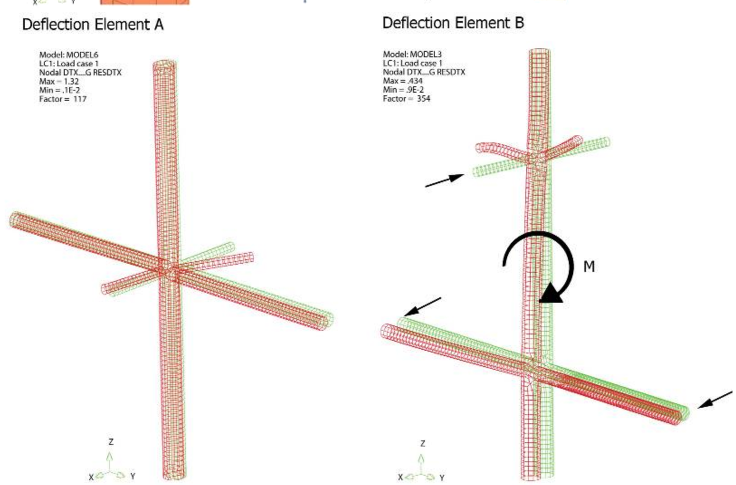


Figure 7.10
Deflection
element A

Figure 7.11
Deflection
element B



On the other hand element B has an asymmetrical geometry which results in a bending force in the main tube. The horizontal cables that stabilize the structure can not be connected at the same height as the arm in the x-direction. This will also reduce the view to the outside.

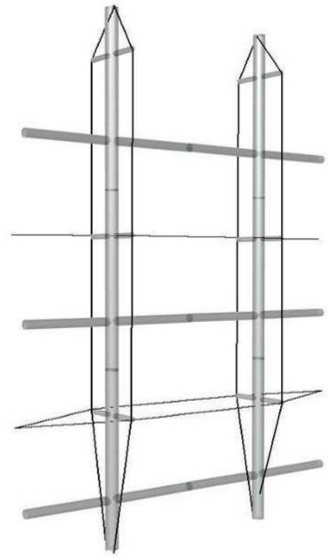


Figure 7.12 Assembled structure from element A

Figure 7.13 Assembled structure from element B

7.4 Geometry façade structure

The chosen variant can be described as follows; the façade construction has a grid of 1,8x,18m. This size is derived from the welding limitations. Elements of this size are manufactured in a lathe and can be annealed in the ovens. This element size is also transportable in large boxes. The first horizontal arms start at 2.1m. This will give a free view to the outside and avoids injuries to people's heads. In the two corners space is reserved for emergency exits.

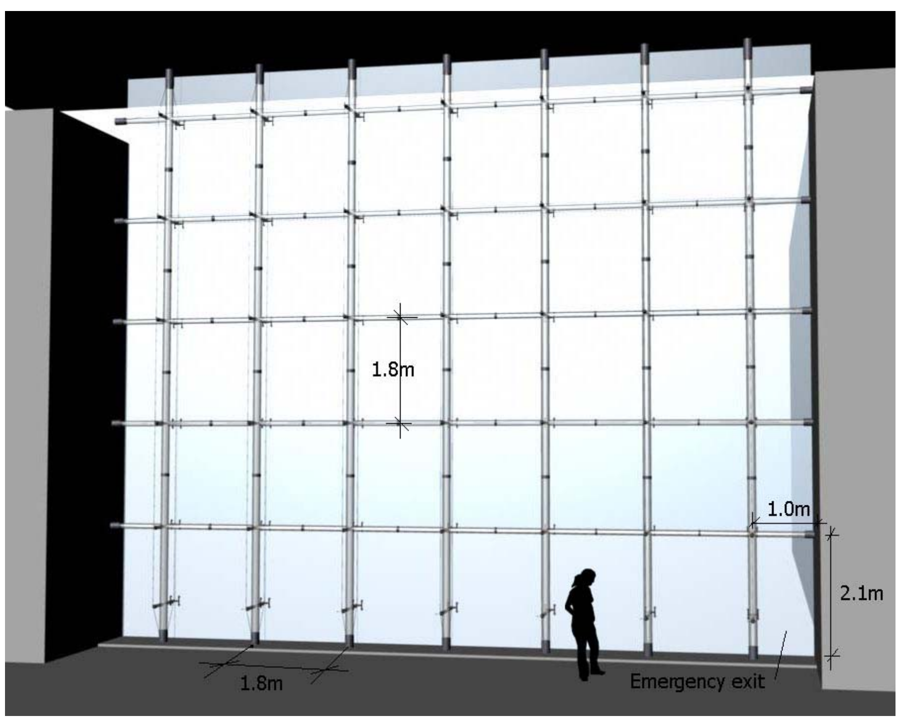


Figure 7.14 Chosen design concept for the application of glass welded elements

H8. Structural analysis

8.1 Structural analysis glass façade structure

The geometry of is build out of different elements. This will result in nodes between the elements. We may not assume that these nodes can be produced as a perfect rigid joint. When pre-stress is not applied, the stability of the structure is not guaranteed. The elements dislocate and cause the domino-effect. When bracing the entire construction it remains stable.

Figure 8.1 Bracing the elements

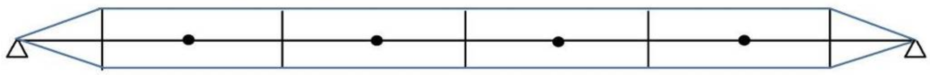
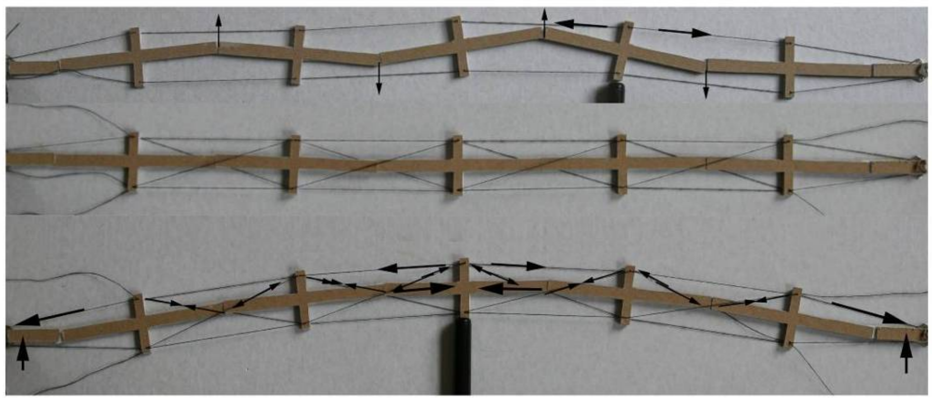
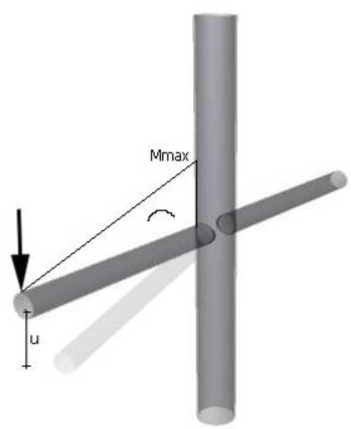


Figure 8.2 Domino effect and the diagonals to stabilize the structure



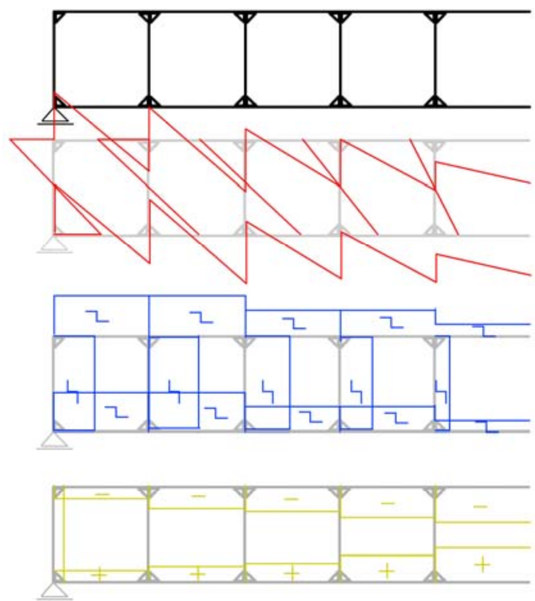
Using bracing in this structure is alien with the introduction of glass welding as a structural application. The characteristics of a welded joint is that it produces a rigid joint. This means that it can accommodate a bending moment.

Figure 8.3 Rigid arm loaded with a force



With the application of stiff tension cables, obtained be pre-stressing, the dislocation of the elements can be avoided. These cables won't be pressed, so that the elements can not buckle. The rigid joint that is created by welding is essential for the stability of the structure. The structure can be compared to a truss without diagonals, called a vierendeel principle, and has rigid corners. In a vierendeel principle occur bending moments, normal forces as well as shear forces. In a truss only normal forces occur. The shear stress is accommodated by the diagonals. In a vierendeel principle the vertical columns need to accommodate the shear stresses.

Figure 8.4 Vierendeel principle



When applying the vierendeel principle to the glass structure a shear force need to be accommodated by the nodes. Due to the pre-stressed cables point *a* will stay in position. The small arm wants to deform in a s-shaped manner. So when looking at the elements of the glass structure, the stiffness of the welded joint is very determining.

Figure 8.5 Forces in the joint

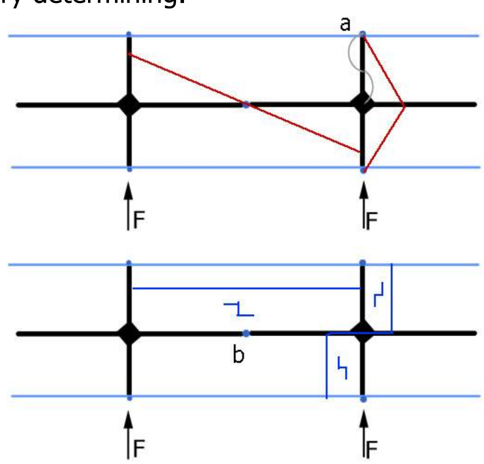
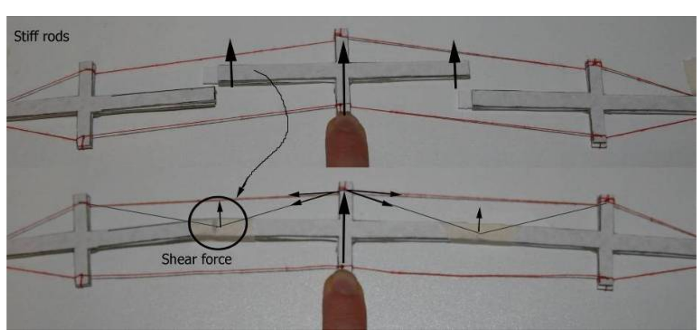


Figure 8.6 Shear force in the nodes



To understand the way the structure behaves and for the detailing of the structure further analyse is necessary. The structure is statically indeterminate and analytical calculations for statically indeterminate structures are available, but demand much work. A computer can be used to solve the calculations. Programs like Diana or other FEM-programs can be used for calculation. In this research only a rough calculation will be done, to give an indication of the profile diameters of the structure. These values can be used as a starting point for further analysis with the computer. First of all the loads have to be determined.

8.2 Determination of the calculation variables

8.2.1 Determination of loads

Two different kinds of loads are distinguished for mechanical analyses, dead load and live load. Dead load is defined by the specific gravity and geometry of the material.
Live load can be subdivided by many different kinds of loads, like snow, wind and people.

In this research the structure needs to accommodate its own dead load and the wind load on the façade.
Dead load is denoted by G and live load is denoted by Q.

8.2.2 Determination dead load

To define the dead load the next formula is used.

$$G_b = A \cdot h \cdot \rho \cdot g \qquad (8.1)$$

8.2.3 Determination wind load

Wind causes pressure and suction on building facades. The wind load differs per day, location, building density and height of the construction. To determine the wind load on a construction, Holland is divided in three parts. The project is located in Delft which means that the normative area is area II.

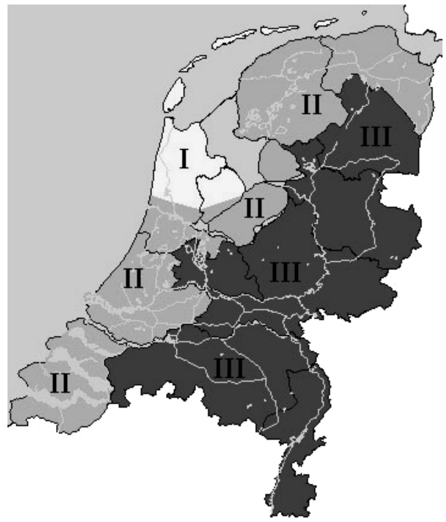
The formula for the determination of the wind load:

$$P_{rep} = C_{\dim} \cdot C_{index} \cdot C_{eq} \cdot \Phi_i \cdot P_w \qquad (8.2)$$

P_w =0.59kN/m^2 Delft is located in region 2 in an urban area.
C_{dim} = 0.95
C_{index}= C_d= 0.8 pressure
C_z= -0.4 suction
C_{eq} and ϕ_i can be neglected because the façade h<50 and h/b<5.

P_{rep} = +0.62kN/m^2 *for pressure*
P_{rep} = -0.40kN/m^2 *for suction*

Figure 8.7
Wind regions of the Netherland



Structural calculations are verified on the ultimate state limit and serviceability state limit. The ultimate state limit is the limit where strength stability and stiffness doesn't comply with the safety. The construction will fail. The load factor for the dead load is 1.2 and life load is 1.5. The serviceability state limit is the limit where the construction is still strong enough but because of its deformation isn't usable anymore. The load factor for all loads is 1.0. See also appendix D.

Figure 8.8
Wind pressure

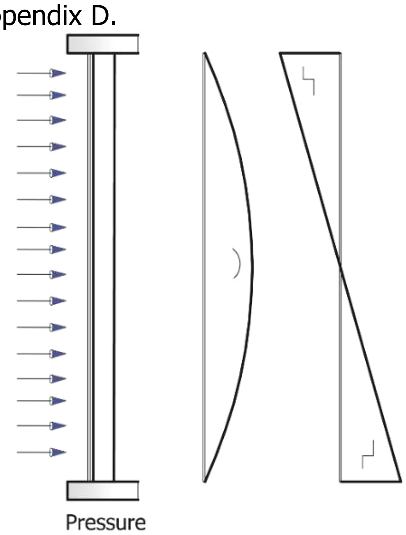
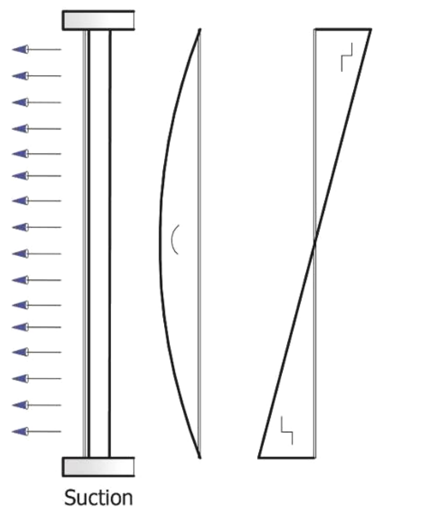


Figure 8.9
Wind suction



8.2.4 Load cases

Ultimate state limit:

dead load	$1.35 \cdot G$
dead load + wind	$1.2 \cdot G + 1.5 \cdot Q$

Serviceability state limit:

dead load + wind	$1.0 \cdot G + 1.0 \cdot Q$

In this case Q is P_{rep}.

Determination deflection

The maximum deflection of a construction can be determined[1] by

$$\omega_{\max} = \frac{1}{175} L \qquad (8.3)$$

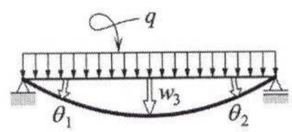
l = 10.000mm

w_{max} *= 58 mm*

The deflection of the construction can be calculated by:

$$\omega = \frac{5}{384} \frac{ql^4}{EI} \qquad (8.4)$$

Figure 8.10
Deflection



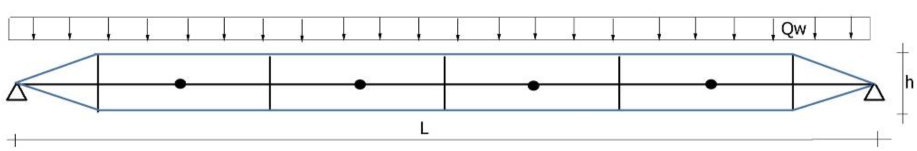
8.2.5 Determination design strength

Requirements in relation to the design strength and the deflection need to be set up for evaluation. The design strength of glass is dependent on several variables. These variables are described in chapter H4 of the literature part. To give an indication about the design strength for the truss, some tests are done. From test the design strength is determined see chapter H15.

8.3 Definition profiles

Pre-stressed cables have not been taken into account. Therefore half the height (h), is used to perform the calculation. See also appendix D and E.

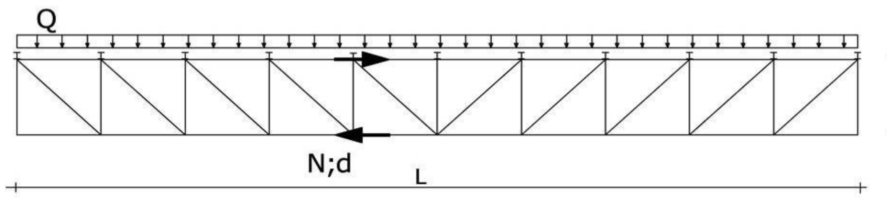
Figure 8.11
Deflection



To determine the load in the structure, the basic principle for calculating a truss is used.

[1] The institution of Structural Engineers Structural (1999), Use of glass in Buildings, London. SETO. p65 (ASTM E1300-94)

Figure 8.12
Deflection



8.3.2 Ultimate state limit main tube

L= 10m
h= 0.79m
$Q_{w,rep,pressure}$= 1.116kN/m[1]
G_{rep}= 0.7kN/m[1] (Assumption for dead load, Duran 150x5)
σ=20N/mm[2]

Ultimate state limit:

dead load $1.35 \cdot G$
dead load + wind $1.2 \cdot G + 1.5 \cdot Q$

$$N_d = \frac{Q_{d;u} l^2}{8h} + deadload$$

$$N_d = \frac{1.7x10.000^2}{8x350} + 830N = 61544N$$

$$\sigma = \frac{N_d}{A} \qquad 20 = \frac{61544}{A}$$

A = 3077mm^2 => Proposal <u>ø150x7mm</u> (3144mm²)

8.3.3 Serviceability state limit main tube

L= 10m
h= 0.79m
$Q_{w,rep,pressure}$= 1.116kN/m[1]
G_{rep}= 0.7kN/m[1] (Assumption for dead load, Duran 150x5)
σ=20N/mm[2]
w_{max} = 58 mm
E = 64000MPa
I= 55849073,57mm^4

Serviceability state limit:

dead load + wind $1.0 \cdot G + 1.0 \cdot Q$

$$\omega = \frac{5}{384} \frac{ql^4}{EI} = 58\text{mm}$$

$$\omega_{max} > \omega_{opt} \qquad \omega_{opt} = \frac{5}{384} \frac{1.12 \bullet 10000^4 \bullet 10^6}{64000 \bullet 55849073} = 40mm$$

40mm < 58mm complies with <u>ø150x7mm</u> (3144mm²)

8.3.4 Buckling check main tube

$$F_e = \frac{\pi^2 E_{glass} I_{glass}}{l_c^2}$$

$$\lambda = \sqrt{\frac{N_d}{F_e}} \Rightarrow \omega_{buc}$$ NEN6770 figure 42

$$\frac{N_d}{\omega_{buc} \cdot A_{glass} \cdot f_{d;glass}} \leq 1$$

$$F_e = \frac{\pi^2 64000 \bullet 8057595}{1800^2} = 1570kN$$

$$\lambda = \sqrt{\frac{55kN}{1570}} \Rightarrow \omega_{buc} = 1$$

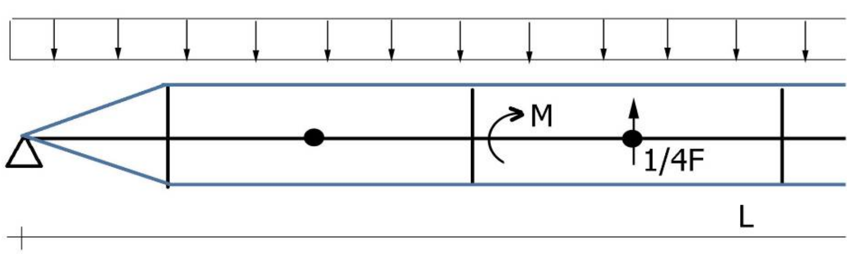
$$\frac{55}{1 \cdot 3144 \cdot 18} = 0.96$$ ≤ 1 ø150x7m complies

8.3.5 Ultimate state limit long arm

$L_{element}$=1.8m
$F_{w;d}$=3.0kN
σ=20N/mm^2

Due to the shear force that appears in the node between the elements, a moment occurs in position of the welded joint.

Figure 8.13
Deflection



$$M = \tfrac{1}{4} Fx \tfrac{1}{2} L_{element}$$

$$\sigma_{\max} = \frac{M \cdot z}{I} = \frac{M}{W}$$

$$M = \tfrac{1}{4} 3000 \ x \ \tfrac{1}{2} 1800$$

$$20 = \frac{675000}{W}$$

W=33750mm³ → Proposal ø100x5mm (W=33960mm³)

8.3.6 Ultimate state limit small arm

$F_{w;d}$=3.0kN
σ=20N/mm^2

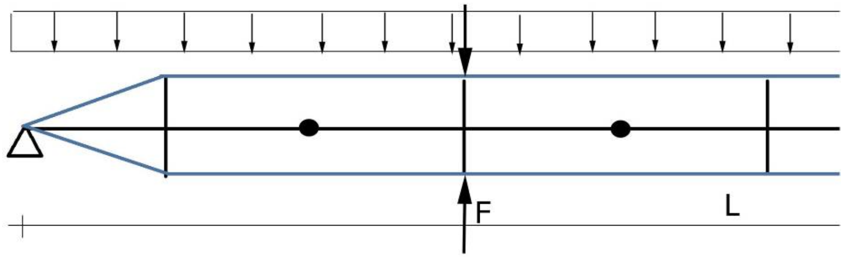


Figure 8.14 Deflection

$\sigma = F_{w;d}/A$
A= 150mm^2 → Proposal ø40x3.2mm (370mm²)

8.3.7 Concluded

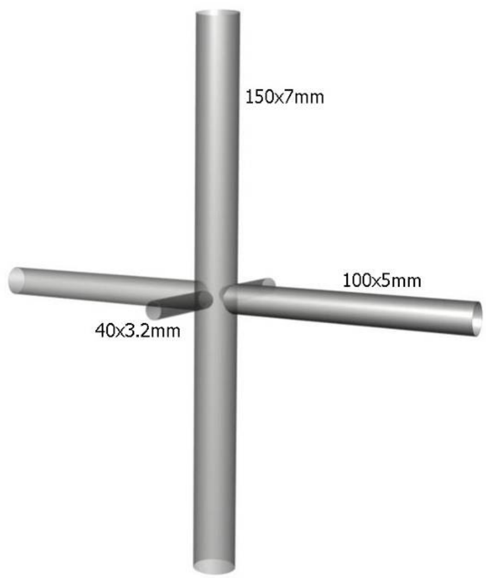


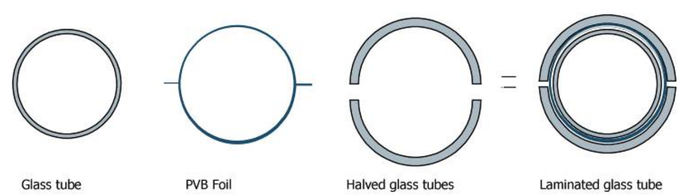
Figure 8.15 Diameters and thicknesses of glass element

8.4 Strengthening possibilities of the glass elements

8.4.1 Lamination processes

People live and work in buildings. A building has a protective function against weather and must protect people from injure. A building's structure must be stable and strong so that safety is guaranteed. This glass façade is not part of the main carrying construction. It has the task to accommodate the wind load and its own dead load. As written in the literature part, glass is a difficult material to predict the strength. Load bearing glass constructions, mainly made out of soda-lime float glass, are laminated and strengthened. The advantage of laminated glass is the positive failure behaviour. The glass panels show cracks but will not fail immediately, so that the glass column remains strength. Lamination of glass tubes can be done in different ways. The first method is using PVB-foil to adhesive the tubes. The lamination process takes place in an autoclave. Under high pressure and temperature a bond will be created between the PVB-foil and the glass tube. The problem of using this method is how to place the foil between the two glass tubes. This technique is applied at the Tower Place in London. The PVB-foil covers one intact glass tube and another glass tube is cut in pieces and two half shells.

Figure 8.16 Lamination process glass tubes



The second method is using a liquid resin. This laminated tube glass column has been researched by Elke van Nieuwehuijzen and opportunities are there. For laminating glass tubes a double walled construction is needed. A resin is inserted in the cavity, which laminates the two glass tubes. The biggest problem of the lamination process is the cure process of the resin. The shrinkage of the resin can cause delimitation at certain places and decreases the transparency of the glass tube. Also according to research done by van Nieuwehuijzen there is a problem in the consistency in the sizes large glass tubes. To match two tubes to create a small cavity is difficult because of the differentials in diameter.[1]

Double walled constructions can be created. In the laboratory ware industry they are manually welded and formed. The building size elements should be made in a lathe and a lathe is limited to certain geometries. Further research should be done about the possibilities of making a large-scale double walled glass element.
Options for using lamination for increasing the strength can be done in several ways.

[1] Nieuwehuijzen, E.J. van. Bos, F.P. Veer, F.A. The laminated glass column, Delft

1. Filling the entire element with resin. A massive column is created this way. The shrinkage of the resin and the coefficients of thermal expansion of both materials should be taken into account.
2. Lamination of the main column. Further analyze must be done to about how to perform the lamination.
3. Using a moulded glass element in position of the node with notches, where glass tubes can be glued and later on laminated with a resin. The nice welded joint will be hidden behind the moulded element.
4. Lamination by PVB-foils, by cutting a welded glass element in half and in pieces. A special autoclave should be designed for these elements. Questions can be posed about the profitability of such autoclave.

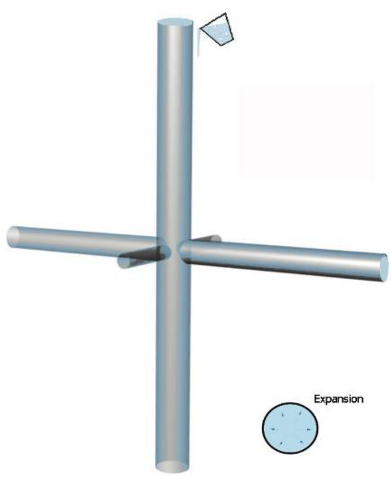


Figure 8.17
Method 1

Figure 8.18
Method 2

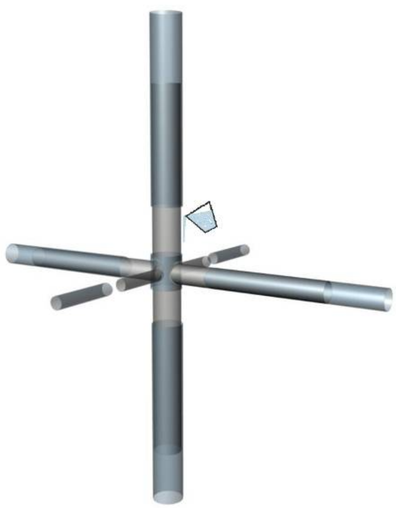


Figure 8.19
Method 3

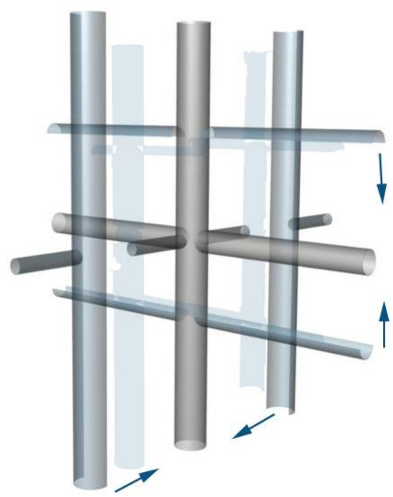


Figure 8.20
Method 4

8.4.2 Strengthening of glass tubes

Strengthening of glass tubes can be done. Using a thermal toughening process, the wall of the tubing can be pre-stressed which results in glass tubing with high resistance to tension and mechanical shock and with still higher resistance to thermal shock. Strengthened glass tubes are available under the name Duratan[1].

Figure 8.21 DURATAN strengthened glass tube

Glass tubes also can get a oil bath, per example $LiNO_3$ at 300°C, while through chemical strengthening glass becomes stronger. The sodium ions are replaced by the smaller lithium ions. A layer of 0.01-1.0mm with a lower coefficient of thermal expansion is created. After thermal treatment above the transformation temperature, T_s, of the glass, the outer layer comes under compression stress. [2] To simple geometries an oil bath can be given. Further research must be done about the limitations of the geometry and chemical strengthening process.
Another method is replacing the sodium ions by potassium ions, so that the outer layer comes under compression stress. Temperature treatment is not necessary with this method, but is a time-consuming method.

Strengthening of glass can also be done by the use of epoxy based coatings, solvent based (complete flaw filling) and water based systems (partial flaw filling).[3]

Two other methods of glass strengthening are enamelling and etching in hydrofluoric acid[1]. Enamelling is covering the glass object with a layer of low expansion glass-enamel. Usually the enamel had a lower softening temperature. After cooling down to room temperature the enamel will cause a compression stress at the glass surface. The compression stress is determined by the difference of coefficient of thermal expansion. High differences will cause cracking in the enamel layer.
Etching of glass with hydrofluoric acids increases the failure strength of glass. The condition is that the pickled surface must be thick enough to remove any surface damage. The glass surface will become opaque.

---

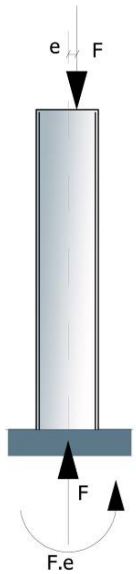
[1] Schott-Rohrglas GmbH. Schott Duratan, Thermally pre-stressed tubing of special glass. Mitterteich.

[2] Heller, P. Ververst, J. Wilbrink, H. (1992) Vademecum voor de glastechniek, Deventer. Kluwer Technische Boeken

[3] Whittle, B.R. Hand, R.J. Ellis, B. (2001) A water based coating for the strengthening of flat glass. University of Sheffiied.

8.4.3 Pre-stressing of glass tubes

Figure 8.22
Moment caused by eccentric placement of the load



Another possibility of introducing safety in a glass construction is to pre-stress the glass tubes. Pre stressing is a method where in advance a compression force is introduced, so that materials that are weak in accommodating tensile stresses, can withstand some tension. By transferring steel cables through glass tubes and anchor them at nodes, afterwards pre-stress them, so that the nodes are pressed to the glass tube. It is necessary that the steel cable is placed in the centre to avoid an eccentric force that can cause bending forces in the glass tube.

H9. Detailing

9.1 Joining principles within the glass welding technology

With the development of using glass welding in the building industry followed by the use of tubular glass elements, the demand for cylindrical connections arises. The tubular shape of the tubes makes it hard to drill holes in it and the accessibility of connections is more difficult. Within the glass welding technology joining of glass tubes is done in several ways. Standard systems are available. These systems can be divided into a. taper systems, b. flange systems, c. bullet systems, d. threat systems.

Figure 9.1 Standard joints in the glass welding industry

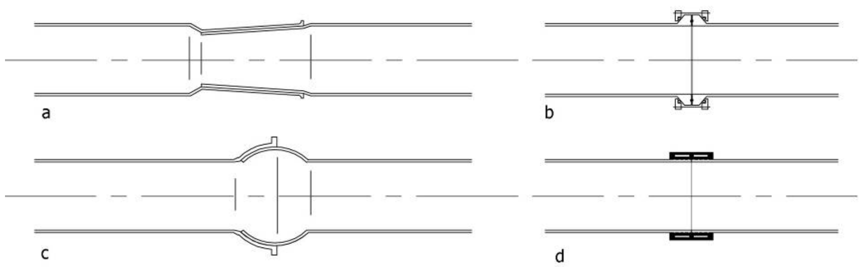


Figure 9.2 Joints in the glass welding industry

Figure 9.3 Ball-joint in combination with inox

	Fixation	**Sealing**	**Available diameters**
Taper system	Tapered edged jacket and core	Grease	5-200mm
Flange system	Clamping of two glass tubes by flanges	Grease, O-ring or Viton (silicon) ring	5-300mm
Bullet system	Bullet and husk that fit within each other	Viton (silicon) ring	<100mm
Threat system	Screw threat is edged at the tubes' ends.	Screw cap	

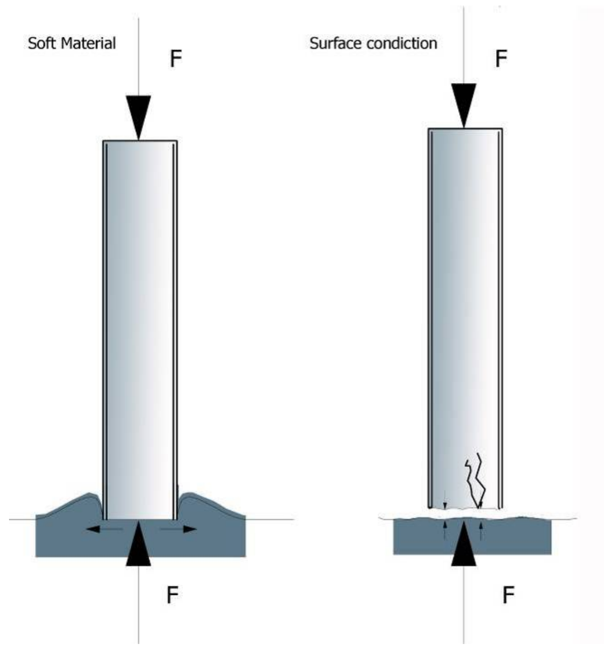
A tubular connection has been created by James Carpenter in the Tower Place in London. Two pressure heads were pressed by a steel post-tensioned rod. See also paragraph 4.7.2

9.2 Research and developments in jointing tubular glass

Glass can not absorb strong tensile forces by any plastic deformation in the atomic structure. It is would not fail under compression force but under tensile peak stresses. Due to wrong design of the supports, by choosing the wrong material, glass often fails in position of the supports. To support glass it is necessary to use a soft material. Glass tubes are made by extrusion and cut with a small hot flame. Afterwards the tube ends are polished with a flame. It might result in a not perfectly smooth end. That is why a soft material is needed to avoid peak stresses at the tubes end. When the material of the support is too soft under high compression it will show creep, due to the exertion of tensile stresses perpendicular to the force. The glass tube will splinter at the end. For high compression stresses a material like aluminium or steel has to be used. To create a support with a hard material it is necessary that the glass tubes end and the surface of the hard material is smooth, especially with steel. Burrs are excepted as long as it does not exceed the elastic deformation of glass. This means the higher the compression force the smoother the surfaces need to be[1].

Figure 9.4 Using a too soft material as support

Figure 9.5 Irregularities at the top/bottom of a glass tube



In the research done by Elke van Nieuwehuijzen, laminated tubular glass columns were subjected to a compression test. For the support she used PMMA. This is a relatively strong and stiff polymer and is transparent. Two support methods were applied. In the first method the prototypes were directly supported on the PMMA. The second method was gluing a PMMA-plug in the inner tube. The forces are transferred by shearing. The edges of glass are usually the weakest because of the finishing methods[2] and by using the second method the edges are free of loading. However the first method resulted in much higher initial failure strength and maximum strength. This is because in the second method the glue was unevenly divided, so that weak and strong parts caused local peak stresses. The PMMA was able, because of its softness, to accommodate the irregularities of the tube's top[3].

---

1 Doenitz, F.D. Laminated Glass Tubes as Structural Elements in Building Industry, University of Stuttgart

2 Veer, F.A. Zuidema, J. (2003) The strength of glass, effect of edge quality, Delft

3 Nieuwehuijzen, E.J. van. Bos, F.P. Veer, F.A. The laminated glass column, Delft

The unevenly distributed adhesive used for creating a support or joint with glass tubes has been researched by Freek Bos. This research is about the glass to acrylic cylindrical adhesive bonds. Difficulties occur during the application and the curing of the adhesive bond as well the bond shape and the differences in the coefficient of thermal expansion of the jointed materials. The first question that arises is how to get the adhesive in the cavity. Different ways are tested and to create an homogeneous bond between the glass and PMMA, Bos managed by using three straws for filling the cavity with adhesive. The curing of the adhesive has to be controlled by a slow and even curing on a rotating disc at a distance of 2,8meters from the UV-light. The biggest problem of using glass and PMMA is the coefficient of expansion of both materials (Borosilicate glass: 3.25×10^{-6} PMMA: 85×10^{-6}). PMMA expands almost 30x more than glass. When the sun starts to shine on the construction, both materials would like to expand, but due to these differences the glass will crack. To permit the PMMA to expand a slit was put in the PMMA part and filled with silicone[1].

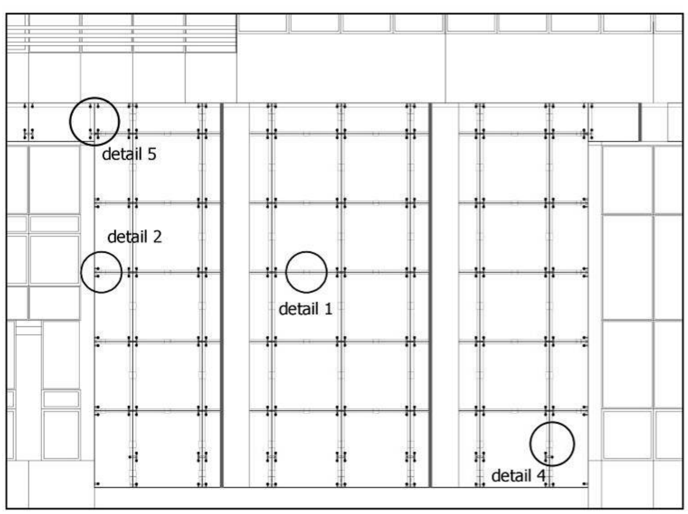
9.3 Detailing of the glass structure

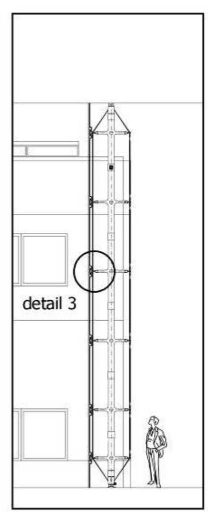
Detailing has to do with constructive and aesthetic values. The new glass construction has to fit within an existing building. Dimensional tolerance has to be taken into account. It has to be sure that the angle of the intersecting tubes is absolutely correct and the welding is flawless. The manufacturer must be able to manufacture to such small tolerances. Louwers glass and ceramic technology explained that the accurateness of glass welding is very precise.
Little dimensional tolerance must be moderated by the joints.

There are many ways of fixating materials. Glass tubes have the difficulty of its shape. The tubular shape is hard to connect because of the inaccessible of the inner side and the difficulty of drilling holes in the glass tube.
Replacement is another issue. Glass is known about its brittle character, so if one element fails it must be replaced by a new one.

Figure 9.6 Front view facade

Figure 9.7 Cross section

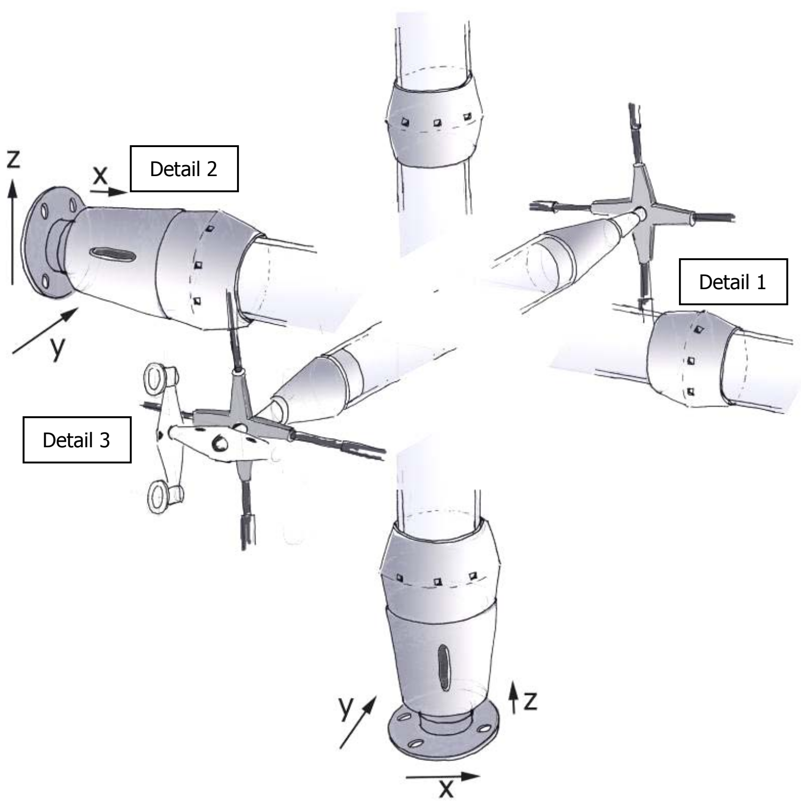




[1] Bos, F.P. Glass-to-acrylic and acrylic-to-acrylic cylindrical adhesive bonds, Delft

	Joint description	Requirements
Detail 1	Fixation of the glass elements	Shear force Torsion Compression Demountable Adjustment possibilities
Detail 2 **Detail 5**	Connection to existing construction Connection to the lower wall	Torsion Compression Demountable Hinged connection Adjustment possibilities
Detail 3	Connection to the glass facade	Compression Suction Demountable
Detail 4	Detail of the emergency exit	High level of transparency

Figure 9.8
All details on one star-shaped glass element



9.4 Detail 1

9.4.1 Fixation of the joint

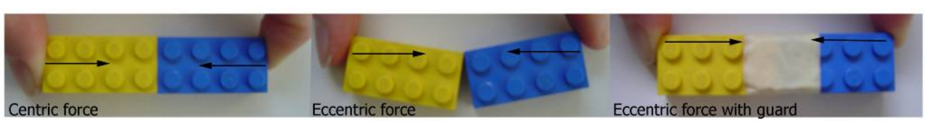
The reason for using PMMA is because of its transparency. The problems that occur through its expansion, could cause failure. Another material that is often used for detailing is aluminium. Aluminium is relatively soft in contradiction to steel and can therefore directly be connected to glass. Between glass and steel a soft material needs to be placed to avoid peak stresses. Steel (210GPa) is stiffer than aluminium (70GPa), but aluminium is much lighter. Next to that aluminium has almost the same stiffness as glass.
The greater stiffness of the aluminium instead of PMMA leads to less material use. Next to that, aluminium has a four times lower coefficient of thermal expansion than PMMA. The high-tech image of aluminium corresponds with the innovativeness of this design.

Aluminium has a relatively smooth surface[1] and can therefore be glued to glass[2]. However the surface roughness of nylon is much smoother than aluminium. Glued connection have an uniform stress distribution in the joint. I contradiction to bolted joints, the complete adhesive bond contributes to the accommodation of the force. Many kinds of adhesive exist and the influence on which one to choose is dependent on several aspects. The time dependency of the adhesive under long-term load, the flowing behaviour of the adhesive, the flatness of the connected materials and the way of curing. Heat curing could be difficult and UV-curing adhesive can be an option. Because the glass elements can be disassembled, the aluminium joint can be glued in the factory.

9.4.2 Adjustment space and replacement joint

Adjustment within a joint is created by a screw-treat and a bolt. The principle is cribbed from the bicycle torque coupling(BTC). These couplings are designed to demount a bicycle and adjustment space in one direction is taken into account. Because of the torque coupling principle, due to the toothed wheel, it is possible to demount the glass elements and to accommodate torsion. Safety pins prevent the toothed wheels from turning, when a force is attempted to the detail. Compression forces will press the toothed wheels onto each other. When the compression force seize eccentric, the guard prevents the detail from scissoring.

Figure 9.9 Centric and eccentric force on a joint



[1] http://www.unsafegrabbars.org/
[2] http://www.dymax.com/products/glass/index.php

With the help of the screw shackle in the guard principle, both glass elements are fixated to each other. A hook spanner can be used to tighten the guard. The guard also contributes to accommodate the shear force, it covers the inner construction and creates therefore an aesthetic joint.

Figure 9.10
Sketch of detail 1

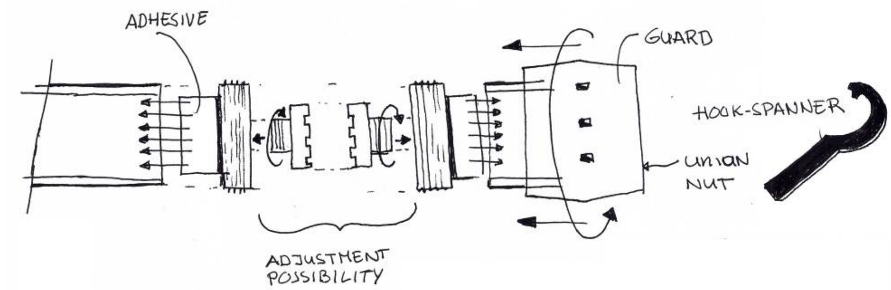


Figure 9.11
Exploded view of detail 1

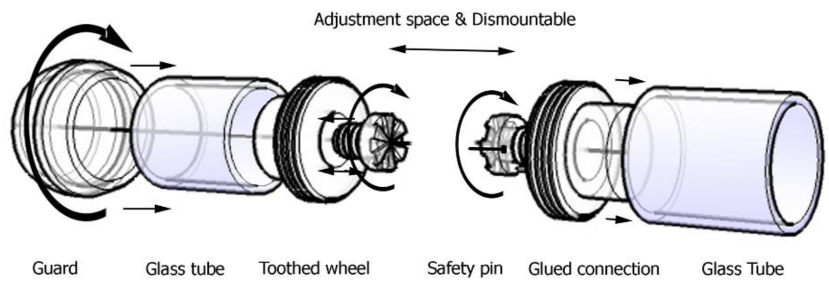
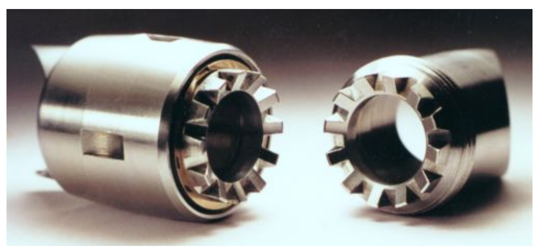


Figure 9.12
BTC Joint



9.5 Detail 2 and 5

9.5.1 Detail 2

The glass structure has to be placed within an existing construction. The dimensional differences of the surrounding concrete structure could leads to fitting problems. Dimensional differences in three directions have to be accommodated by the joints. The support represents a hinge, to prevent an extremely stiff construction. The connection to the glass element has the same end, so that every joint has the same principle in connecting. A cone shaped cover with slots is used to create the aesthetic joint. Through the slots, the tension cables will be fixed.

Figure 9.13 Sketch of detail 2

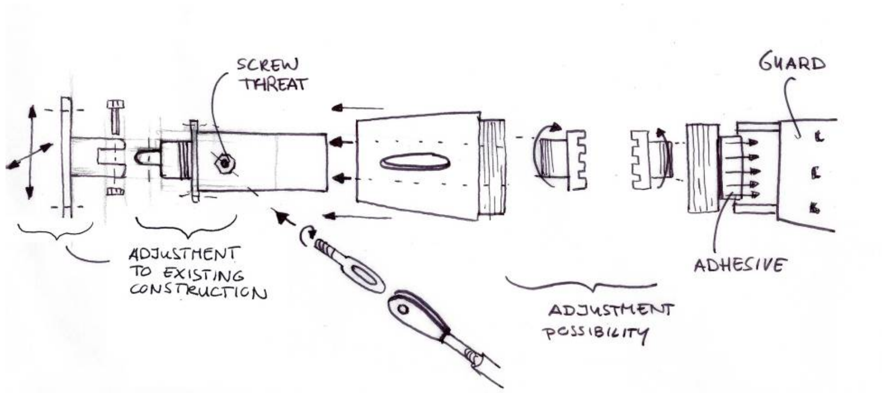
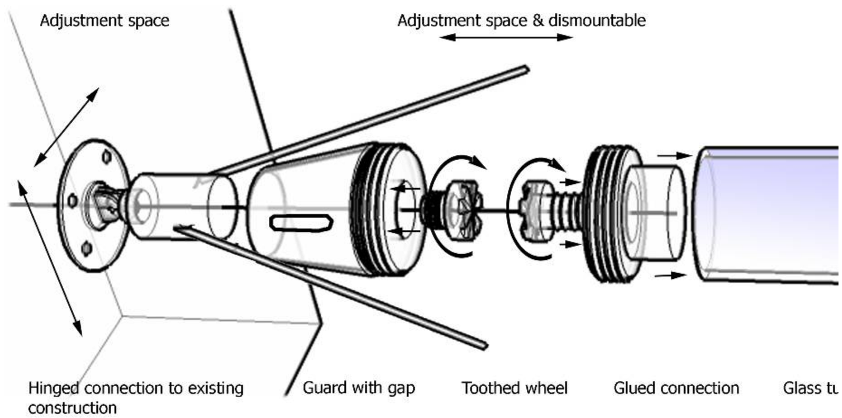


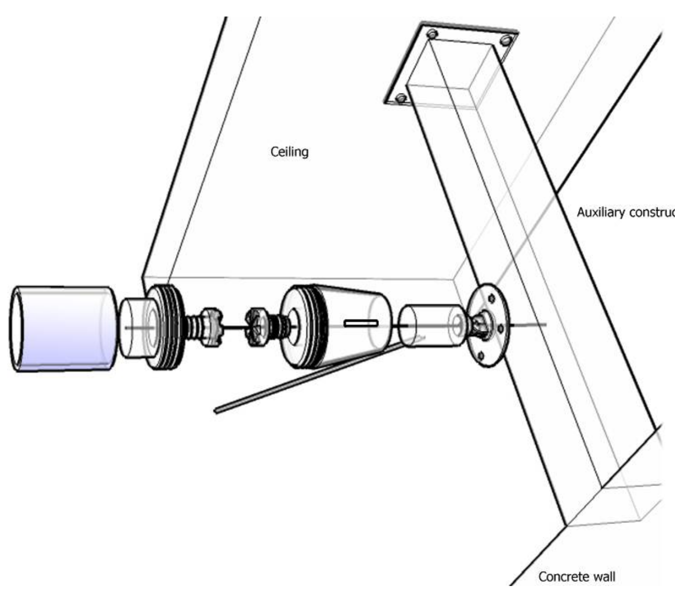
Figure 9.14 Exploded view of detail 2



9.5.2 Detail 5

In position of detail 5, the concrete wall is lower than the ceiling. This was done to create a glass band, to separate the massive block on ground floor of the faculty to the storey-high block. At this part an auxiliary construction was needed to connect the glass elements. The basic principle of the joint is derived from detail 2.

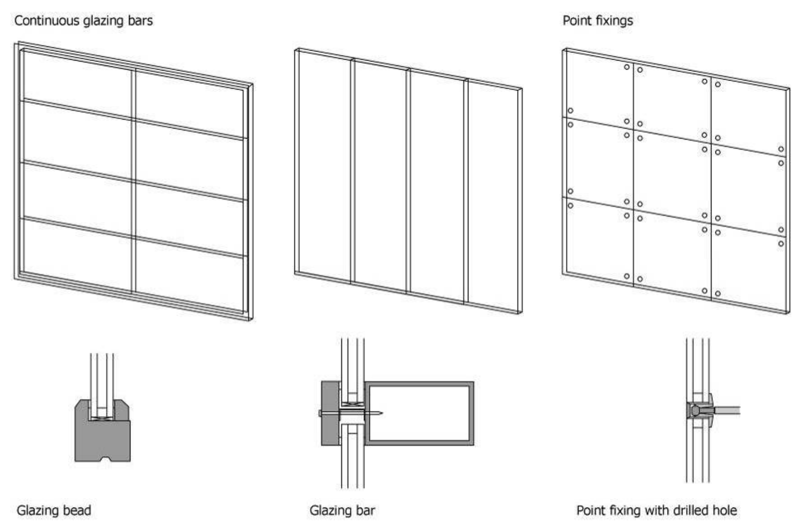
Figure 9.15 Principle for detail 5 in "3d"



9.6 Detail 3

A glass façade can be supported by continuous glazing bars and by point fixings. Within both possibilities several construction details exist. For framing a window glazing bead can be used. A curtain wall usually is built up from glazing bars, because of the easiness of assembling the construction. In standard buildings it is a common used method to make a glass façade. Point fixings are used to increase the level of transparency. Point fixing can be done by clamping glass panes. With this method the fixings do not have to penetrate the glass pane. This introduces a point fixing method where holes need to be drilled. Point fixings are subjected to greater bending en shear stresses than glass panes that are supported continuously. This means that the glass panes should be thicker. When using point fixing it is necessary that the glass façade can follow its natural bending curve. Direct contact with steel should be avoided by adding acrylic or pure aluminium. The position of the drilled holes has a certain tolerance which should be taken into account. For joining an unsupported joint (between two glass panes), sealing profiles and sealants are mainly used.
Within this design project a point fixing system would be suitable. The innovativeness of the application of glass welding and constructing with glass would not fit with a standard and little old fashioned glazing bars.

Figure 9.16 Framing possibilities for glass



All glass panels are fixed without glazing bars. Each panel is supported by 4 point fixing joints. This will result in a more transparent façade and will accentuate the glass construction behind the glass façade much more. This detail is built-up out of different elements, so that the construction is demountable. The ball head in the point fixing of the glass pane is free to rotate. Sealants are applied between the glass panes. The sealed joint at a point fixed glazing is important to assure the space-enclosure.

Figure 9.17
Sketch of
detail 3

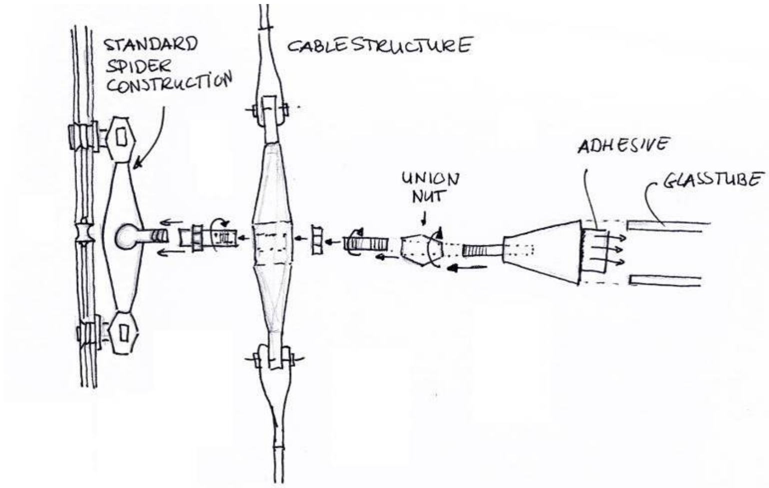
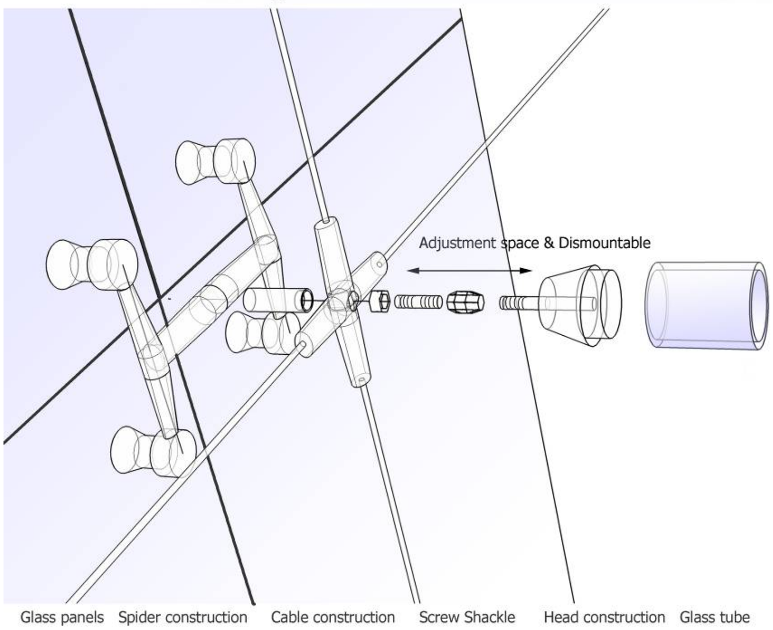


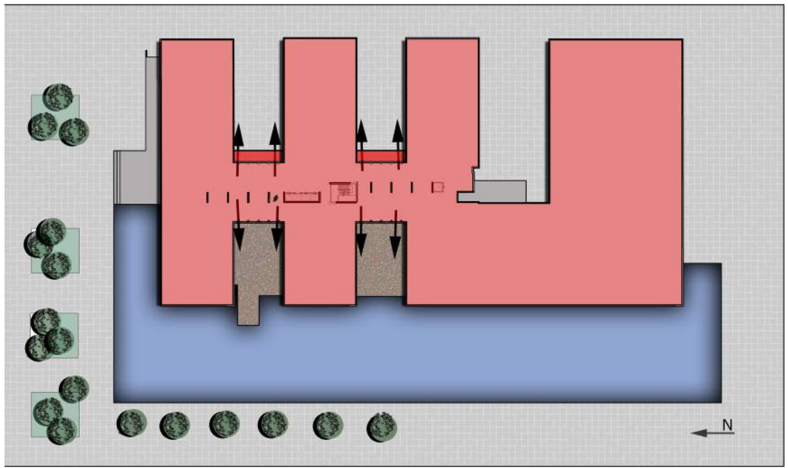
Figure 9.18
Exploded view
of detail 3



9.7 Detail 4

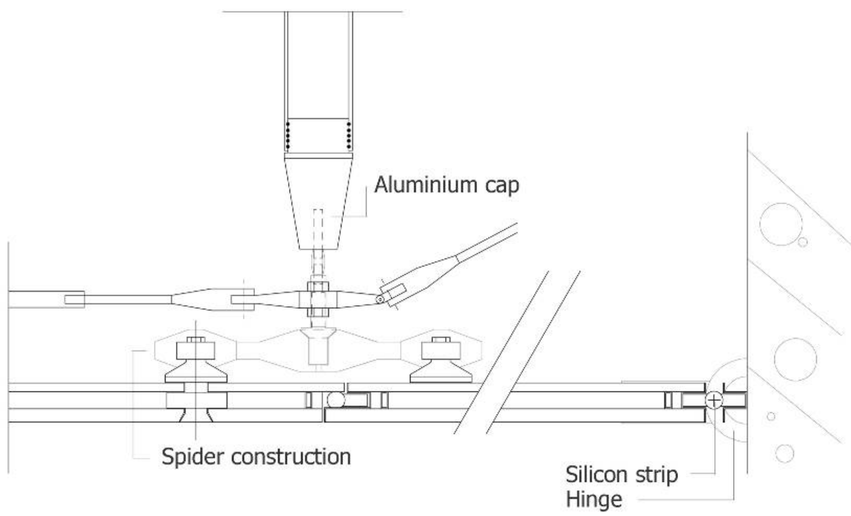
In the central hall of the faculty of architecture are four identical facades. Within every façade, two security doors a placed and should be maintained in the new design. The west side of the building is surrounded by water. On the east side of the building smoker area a situated. The smokers area is placed between the two emergency exits.
Normally a door is placed in a frame, due to security reasons and stiffness. The glass panes in the façade are point fixed and bonded with each other by silicone. This results in a high level of transparency and the fire doors have to fit in this concept.

Figure 9.19 Emergency exits on the ground floor of the faculty of architecture



Using a silicon stop can be a solution that would not reduce the transparency. The glass door is designed by using different length in glass panels to create a rebate to ensure closure.

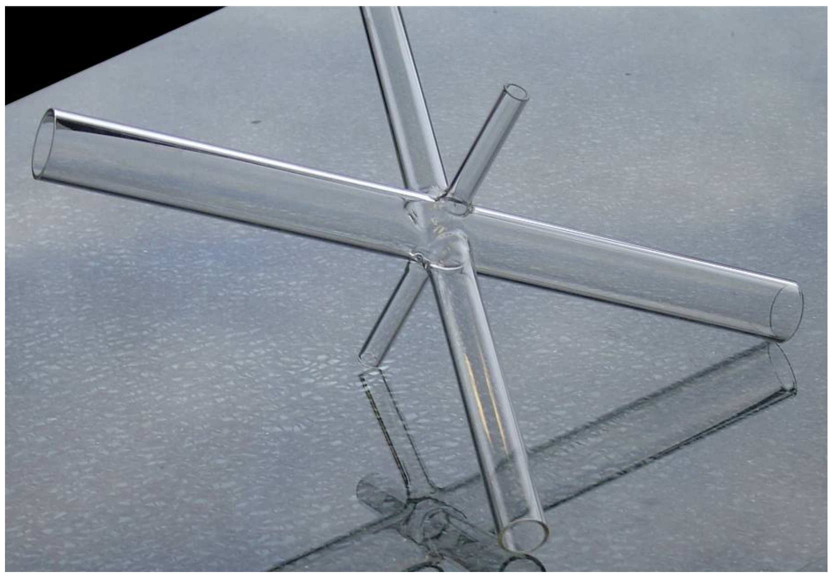
Figure 9.20 Principle for the emergency exit



H10. Design scale model

Scale models are needed to understand the design. A model visualizes the geometry of the design. Henk Lukas of the technical glass department of the TUDelft helped me to make the scale models. The maximum sizes of the models is restricted to the size of the present lathe and the annealing oven. The proportion of the welded joint and the sizes of the glass tube is not linear. A small model will show a relatively larger radius in position of the weld. This has to do with the size of the torch, a relatively larger surface will be heated. By transferring air through the tube a bubble can be blown at the heated part. The 3d star shaped scale models have to be welded in a lathe, because the final elements only can be made in a lathe. To weld the tubes in a lathe an auxiliary construction is needed and has to be designed, see appendix C.

Figure 10.1 Star-shaped scale model



H11. Material research

11.1 Introduction

The hot shaping and glass welding processes are reasonable new in the building industry. It is mainly used in chemical industry for small experimental setups. The scale of elements in the building industry is much larger and constructions should be resistant to several kinds of loads. Due to the brittle character of glass, it will break without warning. To guarantee people's safety it is necessary to know the mechanical properties of the construction and its joints.

In earlier research by Freek Bos, 4-point bending tests have been conducted on butt-welded borosilicate glass tubes. These welded joints were in axial direction of the tube and most of them are located in the middle, but some at 1/3 of the length. There welded specimen are compared to a single piece of glass tube. The results of this research show that the welded joint was not the weakest link. The bending tensile strength of non-annealed glass is higher than the specimen without a weld. The strength of welded specimen that were annealed was a slightly lower than the one piece specimen. [1]

Research on the application of using glass tubes for columns has been done by Elke van Nieuwehuijzen. Two borosilicate glass tubes with different diameter have been placed within each other and are laminated with a liquid resin monomer. The column could carry 200% of the initial failure load and shows that after the first crack still had a load carrying capacity.[2]

In this chapter the mechanical and visual properties of welded glass tubes will be analysed. To guarantee the possibilities of form freedom in glass structures many kinds of weld can be made. From the concept of the design, described in chapter H6, welded tubes and welded T-joints will be tested. The normative forces for the joints will be calculated manually and analysed by the help of the finite element method. The specimens for testing are made of Duran borosilicate glass. This type of glass is usually used in welding processes. It has a low coefficient of thermal expansion and is therefore easier to weld. The specimens are welded by Louwers Glastechniek in the Netherlands.

11.2 Goal definition

The goal of this material research is to give insight into the strength of welded glass joints and define the design strength for the final design. This research should also contribute to the scientific research of using glass as a load bearing material, focusing on a practical solution for the usage of glass welding techniques in the building industry.

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[1] F.P. Bos, F.A. Veer, (2007). Bending and buckling strength of borosilicate glass tubes, Delft.

[2] Nieuwehuijzen, E.J. van. Bos, F.P. Veer, F.A. The laminated glass column, Delft

11.3 Boundary conditions

The material research on welded glass will be focused on the visual quality of the joints, the accurateness of the dimensions of the joints, the strength of the welded glass and the break patterns.

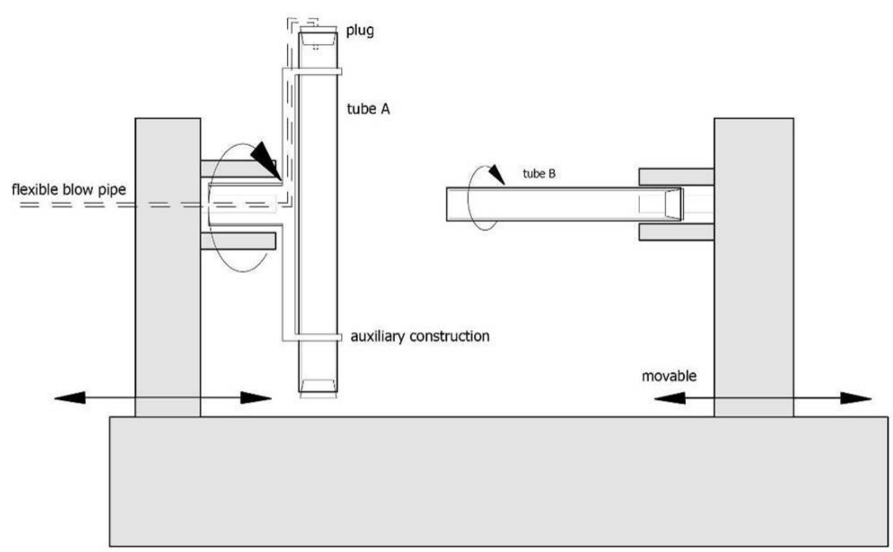
11.4 Theory

11.4.1 Manufacturing process

In this research all specimen have been manufactured partly manually and with the help of a lathe. This is highly labour intensive and time consuming. Since glass welding is used for the development of small objects, a new concept for a manufacturing process of building size elements has to be developed to make it economically achievable.

All specimen are made by sawing the standard 1.5m tube into appropriate lengths. The specimen are placed in a lathe and while turning heated with a gas-oxygen welding torch. When the glass has reached the glass transmission temperature, a bubble is blown at the welded part of tube A. The bubble is cut open and the end of tube B is heated. When both parts are viscous enough they are pressed together. By adding air into the tubes a joint is made. With the help of graphite tools and a blow hose the welded joint can be deformed into the right shape. For the manufacture of the T-joints an auxiliary construction is needed. After the production, the specimen are controlled cooled down and finally annealed.[1 2]

Figure 11.1 Welding of t-joints in a lathe



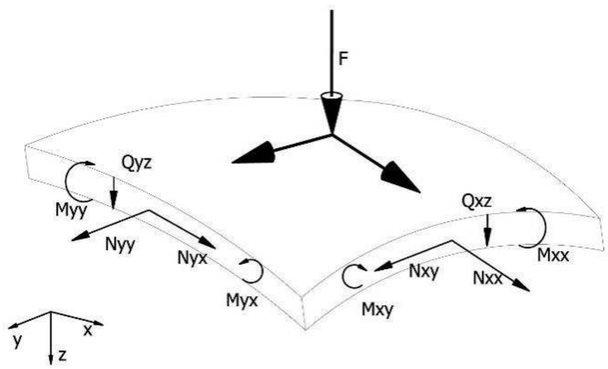
[1] East Carolina University's Glassblowing services, Scientific glassblowing Basics, East Carolina. http://www.ecu.edu/glassblowing/gb.htm
[2] Lis Leiden

11.4.2 *Stresses in a body*

A construction is loaded and needs to accommodate the forces. The kind of stresses that appear in a construction are dependent on the way of loading. The possible stresses in a construction are shear stresses, normal stresses and bending stresses.

Shell elements are three dimensional construction elements. The characteristic of shell elements is that the thickness is small in relation to the other two dimensions. This is typical for a cylindrical shape. The shell elements have the purpose to accommodate the loads. The force loads may act in any direction between perpendicular to the surface and in the surface and accommodates these forces by the means of the membrane forces (Nxx, Nyy, Nxy) that though bending, results in bending and twisting moment.[1]

Figure 11.2
Stresses in a shell element



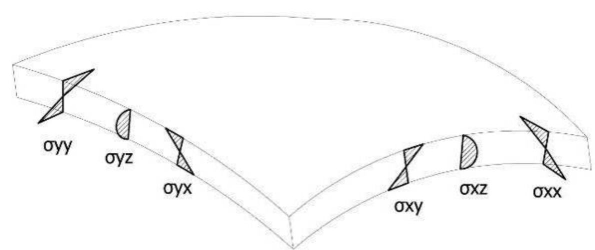
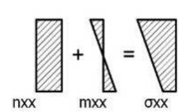


Figure 11.3

The total stress can be written by:

$$\sigma_{xx} = n_{xx} + m_{xx} \qquad (11.1)$$

Figure 11.4
Total stress



For shell elements, which have a thin surface, the next formula is used:

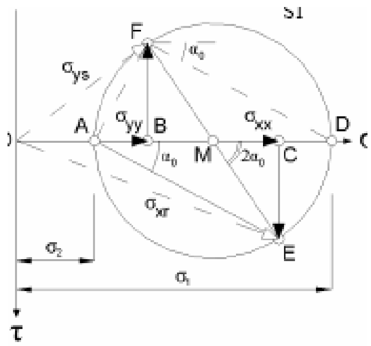
$$\sigma_{xx,\max} = \frac{M_{xx}}{\frac{1}{6}t^2} \qquad (11.2)$$

[1] Beranek, W.J.(1975) Vlakke Constructiedelen Elasticiteitstheorie, Technische Hogeschool Delft.

$$\sigma_{xx} = \frac{N_{xx}}{t} \tag{11.3}$$

With the help of the principle stresses it is possible to read out the pure tensile and compression lines. The pure tensile en compression stresses are in the same direction of the line. This means that in the vertical cross section there are also shear stresses. To define the principle stresses the circle of Mohr is used. σ_1 is the maximum (most tensile) principal stress, σ_3 is the minimum (most compressive) principal stress.

Figure 11.5
Circle of Mohr



11.4.3 Formulas

Bending:

$$\sigma_{\max} = \frac{M \cdot z}{I} \tag{11.4}$$

Pure compression:

$$\sigma = \frac{F}{A} \tag{11.5}$$

Buckling force:

$$F_k = \frac{\pi^2 EI}{l_k^2} \tag{11.6}$$

Shear stress:

$$\sigma_{xy,\max} = \frac{V \cdot S_0}{b \cdot I} \tag{11.7}$$

Moment of inertia for rectangle shapes:

$$I = \tfrac{1}{12} bh^3 \tag{11.8}$$

Moment of resistance for rectangle shapes:

$$W = \tfrac{1}{6} bh^2 \tag{11.9}$$

Moment of inertia for tubes:

$$I_{tube} = \tfrac{1}{4}\pi (r_{bu}^4 - r_{bi}^4) \tag{11.10}$$

Moment of resistance for tubes:

$$W_{tube} = \tfrac{1}{4}\pi \cdot \left(\frac{r_{bu}^4 - r_{bi}^4}{r_{bu}}\right) \tag{11.11}$$

Surface area for tubes:

$$A_{tube} = \pi (r_{bu}^2 - r_{bi}^2) \tag{11.12}$$

11.4.4 Diana

A graphical program for analyzing stresses in a construction is FEMGEN and FEMVIEW, part of the FEM calculation program DIANA. First the model geometry has to be defined. To calculate a model it is necessary to indicate nodes. By subdividing the model in elements by adding a mesh, the model can be calculated by the Finite Element Method. Each element is linked by nodes and for these nodes values can be calculated to estimate the stresses and deflection of the construction.
The Diana output of the principle stresses is S1 and S3.

The next steps need to be undertaken in Diana:

1. Definition of the model geometry
2. Mesh generation
3. Adding material and physical properties
4. Defining loads
5. Defining constraints
6. Performing the analysis
7. Interpretation results

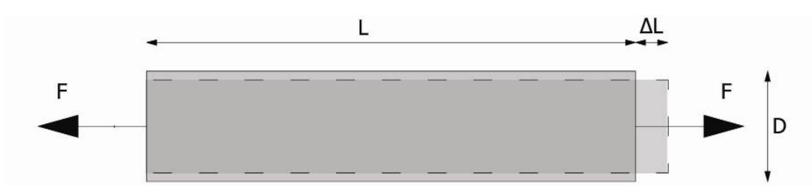
A material and a thickness can be given to the surfaces. The local x- and y-axis of the elements point in the direction of the material and the z-axis is the thickness. The constraints are expressed by giving the fixed directions.

11.4.5 Strain Gauges

Strain is the amount of deformation of a body due to an applied force. More specifically, strain (ε) is defined as the change in length, as shown in Figure 11.6 below.

$$\varepsilon = \frac{\Delta L}{L} \qquad (11.13)$$

Figure 11.6
Strain



Strain can be positive (tensile) or negative (compressive). In practice, the magnitude of measured strain is very small. Strain is often expressed as µ-strain, which is e x 10^{-6}.

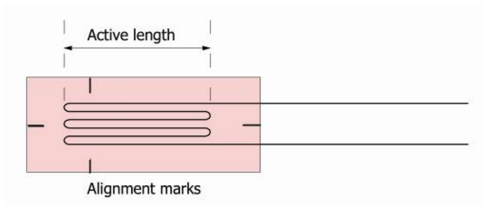
When a bar is strained with a force, the Poisson Strain causes the change in cross-sectional area. The magnitude of this lateral contraction is a material property indicated by its Poisson's Ratio. The Poisson's Ratio (v) of a material is defined as the negative ratio of the strain in the transverse direction (perpendicular to the force) to the strain in the axial direction (parallel to the force). The Poisson’s Ratio of glass is 0.2.

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{longitunal}} \tag{11.14}$$

There are several methods of measuring strain. The most common is with a strain gauge, a device whose electrical resistance varies in proportion to the amount of strain in the device.

The metallic strain gauge is used for measuring the strain during testing. It consists of a very fine wire in a foil. This foil is the carrier, which is directly attached to the specimen with CE-glue. The strain experienced by the test specimen is transferred directly to the strain gauge. This responds with a linear change in electrical resistance. It is very important that the strain gauge be properly mounted onto the test specimen so that the strain is accurately transferred from the test specimen, through the adhesive and strain gauge backing, to the foil itself.

Figure 11.7
Strain gauge



A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon} \tag{11.15}$$

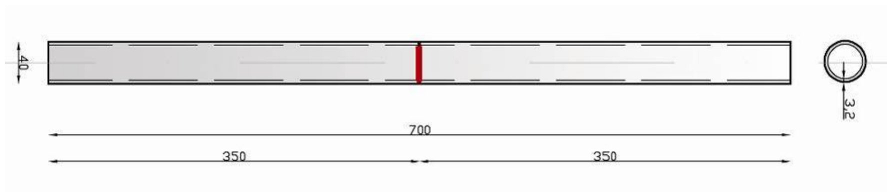
The basic bonding procedures:
1. Cleaning the surface with acetone
2. Marking out the placing position of the strain gauge
3. Re-cleaning the placing position
4. Mounting the stain gauges with tape and CE-glue
5. Removing the tape
6. Check if strain gauges is properly mounted
7. Soldering lead wires to the strain gauges through connecting terminals
8. Connecting the connecting terminals to an amplifier

H12. Experimental research on butt welded glass tubes

12.1 Introduction

To define the strength of welded glass, 19 butt welded glass tubes are tested. The size of the tubes is related to building element dimensions. All glass tubes are from the same production line and the standard available length of the glass tubes is 1.5m. The length of the specimen is determined so that two test objects can be made out of one standard tube. Each specimen is made out of two tubes with a length of 350 mm. The welded joint is located in the centre. The tubes have a diameter of 40 mm and a thickness of 3.2 mm.

Figure 12.1 Geometry specimen 4p bending test

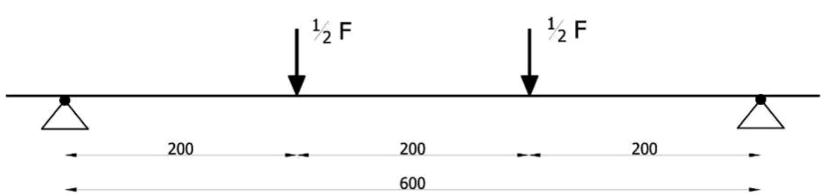


All specimens are tested in a ZWICK Z010 and with Test Expert software. The welded glass tubes are subjected to a 4-point bending test. This test method consists of two supports and two loading pins. In the zone between the loading pins lies the maximum moment. Instead of a three point bending test, with only one loading pin, the 4 point bending test produces a larger zone of maximum stress. This way it is possible to find a difference between the welded joint and its heat effected zone and the unprocessed glass tube. Two specimens are mounted with strain gauges to give an indication about the stress distribution of a glass tube. This chapter describes the undertaken steps and the results of the test.

12.2 Diana Input

To get insight into the stress distribution of tubes, the test setup is first generated in Diana. These results form the starting point of the input of the test rig and for analyzing the failure mechanisms and comparing the results of the strain gauge test. The steps that are undertaken in Diana are described in this paragraph. First the expected failure force has to be calculated.

Figure 12.2 Scheme test setup



Expected failure force:
Assumption stress: σ ≈ 45 N/mm²

$$I_{tube40} = 63100$$
$$M_{\max} = \tfrac{1}{2} F \cdot 200$$
$$\sigma_{\max} = \frac{M \cdot z}{I}$$

<u>F= 1.4kN</u>

12.2.2 Definition of the model geometry

With the help of the shape command, a cylinder and three planes are created. By intersecting these shapes, surfaces are made to define the tube.

Figure 12.3 Model geometry Diana

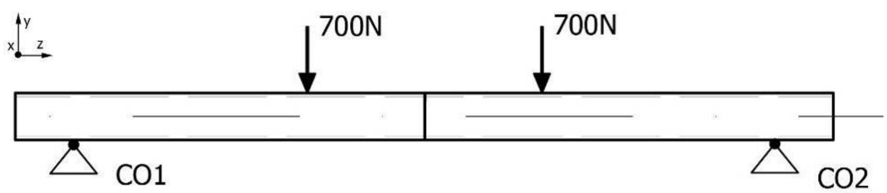
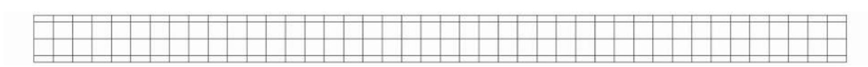


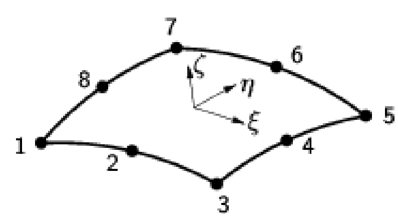
Figure 12.4 Mesh



12.2.3 Mesh and properties

The QU8 CQ40S element has 8 knots and is a curved shell element. This mesh is applied, because shell elements can accommodate forces perpendicular and parallel to its surface.

Figure 12.5 Mesh CQ40S



Material properties	Young's modulus	64000 MPa
	Poisson's ratio	0.2
Physical properties	Thickness	3.2 mm
Loads (force)	700N	
Constraints	CO1	Y
	CO2	Y

12.3 Diana Output

The most important output from Diana are the principle stresses, but to understand the stress distribution completely, all stresses, membrane forces and bending moments are presented in a graphical way. The deflection and principle stresses are shown here under. In appendix G the complete stress distribution of glass tubes is summarized. The maximum principle stress S1 is in position of the support.

Figure 12.6
Reaction force

Figure 12.7
Deflection

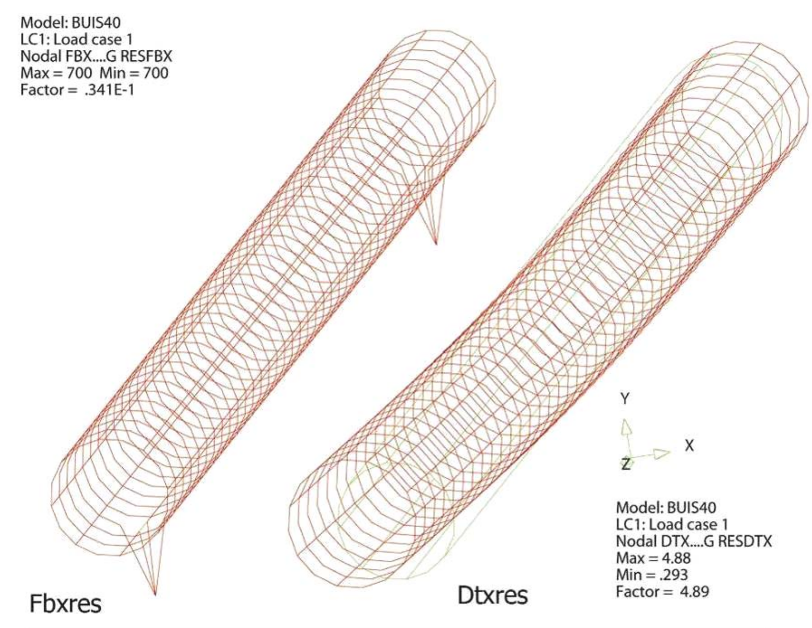
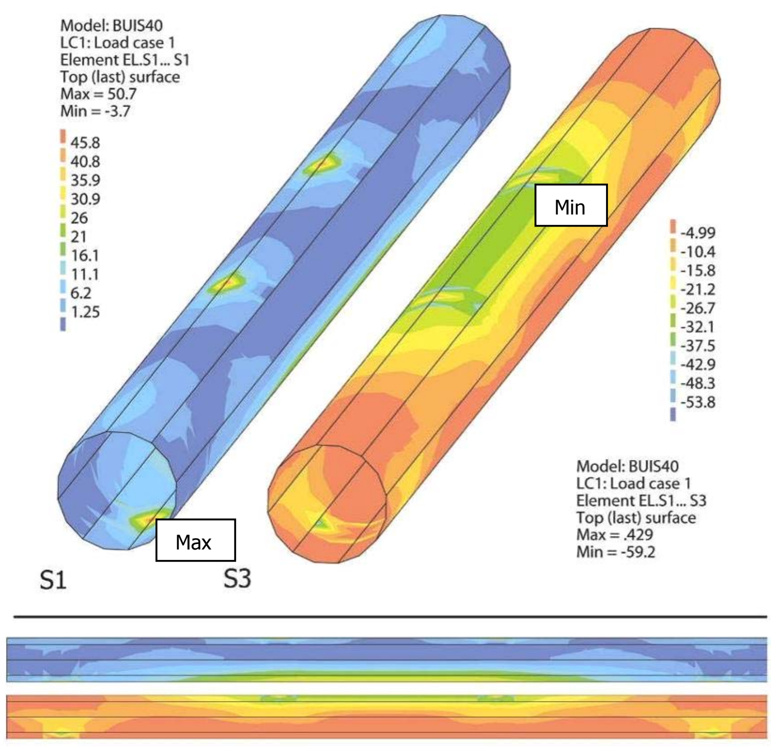


Figure 12.8
Output S1

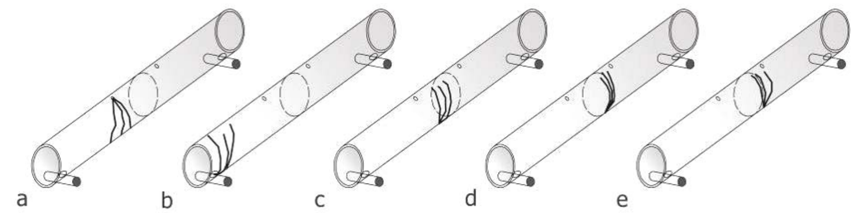
Figure 12.9
Output S3



12.4 Failure mechanisms

Glass fails under tension. There are different ways on how elements can fail. The failure mechanisms together with the FEM calculations will give a better insight into the behaviour of glass tubes subjected to a 4-point bending test. The expected failure mechanisms are summarized here under.

Figure 12.10 Failure mechanisms

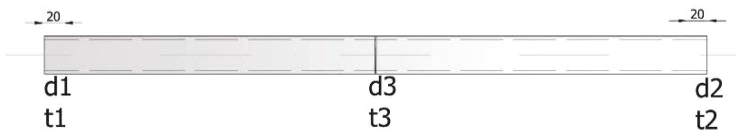


a. Failure due to high stress at force point.
b. Failure due to stress at the support, from Figure 12.9 the principle tensile stress is maximal at the force point
c. Failure due to maximum deflection in the maximum stress zone
d. The welded joint might be the weakest link in the glass tube
e. Failure in the heat effected zone. It might infect the strength of the glass tube, if after annealing not all stress is flowed.

12.5 Geometry Inspection

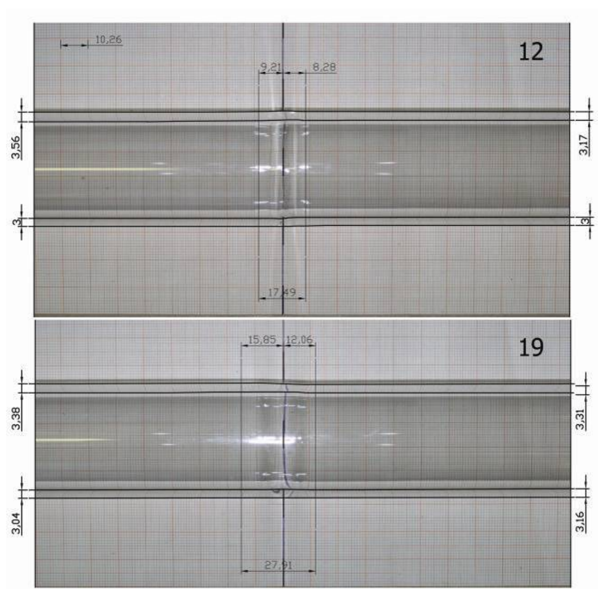
The dimensions of the glass tubes, given in Figure 12.11 , are measured with a digital vernier caliper. Because a cylinder has a round shape, it means that between the different angles there might be a slight difference in diameter. Every point has been measured for two times. The dimension of the inner diameter has a variation, because of its curvature. Because the differences are, due to the exactness of the digital vernier caliper, very small, this little deviation is excepted.

Figure 12.11 Measurements



To give an indication of the size of the heat effected zones and the thickness of the tubes at the weld, the tubes are placed on arithmetic paper and pictures are made. Afterwards the pictures are analyzed in AutoCAD. After measuring the test objects all specimens were wrapped up in plastic to avoid glass splinters to fly while testing.

Figure 12.12 Inspection of specimen 12 and 19 in AutoCAD



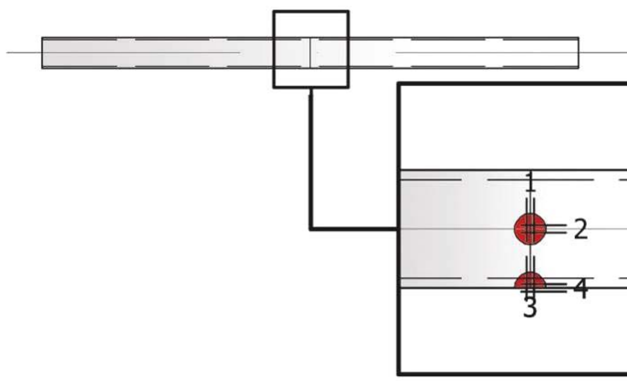
	Average	Standard deviation %
$d_{outer(d1,d2,d3)}$ (mm)	40,12	0,28%
$d_{inner(d1,d2,d3)}$ (mm)	33,64	0,40%
A (mm^2)	374,89	1,50%
I (mm^4)	64268,63	1,60%
HEZ (mm)	19,71	21%

Table 12.1 Summary of the dimensions

12.6 Strain gauges

Test object 19 and 20 were tested with strain gauges. The two double strain gauges were used to measure the strain at the most interesting places. One is placed in the neutral line. It will measure the cylindrical deformation. The other one is mounted at the maximum stress zone. The gauge factor of the used strain gauges are 1:2.07 and 2:2.07. The gauge resistance is 120 Ω.

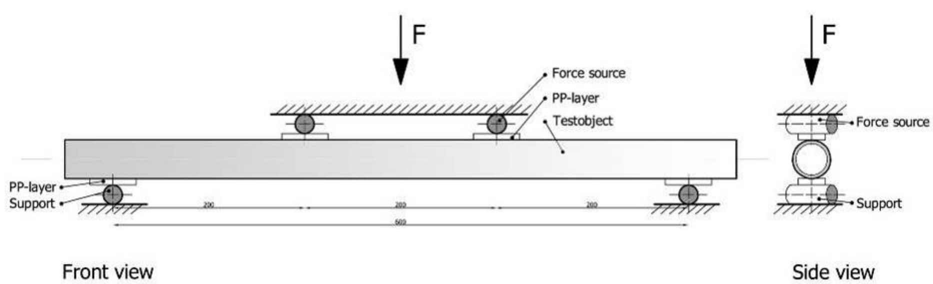
Figure 12.13 Position of the strain gauges



12.7 Design test setup

The 4-point bending test is a standard test method. Standard test rigs for 4-point bending tests are available. Between the force sources and supports an intermediate layer is placed.

Figure 12.14 Design 4-point bending test



12.8 Testing

The support separation was manually set on 600mm and the force source separation at 200 mm, 1/3 of the span. Before starting testing, data of the specimen and the test are inserted in the test program TestExpert. On the supports and the force sources polymers are placed to avoid direct contact with the steel. Tape is used to retain the glass tube from rolling.

First the glass tubes 19 and 20 are tested. These are mounted with strain gauges. The strain gauges are connected to the amplifier. The displacement of the test rig is set on 0.5mm/min and slowly moved up to 0.8 mm/min and later on to 2 mm/min.
Before testing the glass tubes mounted with strain gauges, a glass test tube of 25mm diameter was tested, to evaluate if the experiment setup and amplifier works.

Figure 12.15
Test setup
4-point bending test

12.9 Experimental results

12.9.1 Results 4-point bending test

The results of the 4-point bending test show a higher bending tensile strength than soda lime float glass.[1] The edges of flat glass are normally the weakest link in a glass construction because of the cutting process. A glass tube is not tested on its edge, so this may be an explanation for the higher values of strength.
The results of this test are much lower that the results obtained by Freek Bos[2]. In this test tubes were tested that have the size a building-size elements. The size of the test objects has an influence to the results, because glass has many microscopic cracks scattered on its surface. When the surface gets bigger, the probability of that object failing gets greater.[3] Remarkably is that the tested tubes mounted with strain gauges have a quite low strength.

---

[1] Appendix Test 1

[2] F.P. Bos, F.A. Veer, (2007). Bending and buckling strength of borosilicate glass tubes, Delft.

[3] Schittisch, C. Staib, G. Balkow, D. Schuler, M. Sobek, W. (1999) Glass construction manual, Basel. Birkhäuser.

Zwick test	Testobject	F{lo max}N	M_{max} (Nmm)	σ_{max} (N/mm^2)
CE04 1	19	1418,41	141841	44,69
CE05 2	20	743,9	74390	23,14
4	16	2321,42	208927,8	65,59
6	8	2655,5	265550	83,94
7	7	2516,33	251633	78,94
8	11	2408,8	240880	76,11
9	6	1937,6	193760	60,95
10	5	1714,95	171495	53,40
11	9	2608,04	260804	82,13
12	1	1653,01	165301	50,85
13	10	2182,96	218296	68,22
14	3	2231,14	223114	68,05
15	2	2238,23	223823	68,74
16	4	2171,87	217187	67,74
17	12	2097,32	209732	64,72
18	13	2890,33	289033	92,05
19	14	1712,36	171236	52,75
20	15	2090,75	209075	65,76
21	17	778,95	77895	24,94

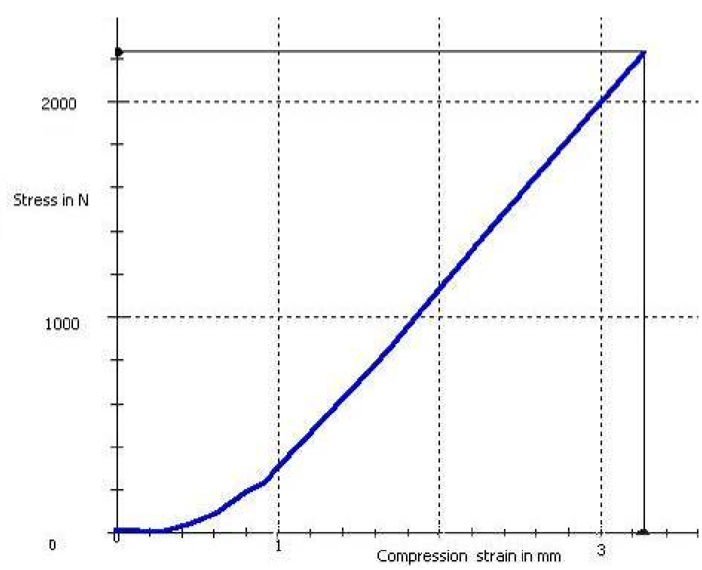
Table 12.2 Results of the 4-point bending test

	F{lo max}N	σ_{max} (N/mm^2)
Average	2019,57	62,77
SD	577,74	18,14
SD%	29%	29%

Table 12.3 Summarized results of the 4-point bending test

The graph shows a linear elastic curve. The beginning of the curve is slightly curved, because of the accommodation to the test rig.

Figure 12.16 Graph 4-point bending test, test #4



12.9.2 Results strain gauges

Stresses in position of the strain gauges can be calculated by

$$\sigma = E\varepsilon \tag{12.1}$$

The results from the first strain gauge correspond to the calculated variant in Diana. Strain gauge #4 shows the stress at the maximum stress zone. The maximum stress is 46N/mm^2 for specimen 19 and 22N/mm^2 for specimen 20 in the tensile zone. This is comparable to the results obtained by calculation, see The strain gauge #1 and #2 are place in the neutral line. The stresses at this point are nil. The difference at #1 between tensile stress at Ce04 and compression stress at Ce05 can be explained by the manually mounting of the strain gauge. But these are very small, so it can be neglected.

Figure 12.17 Comparison CE04 and CE05

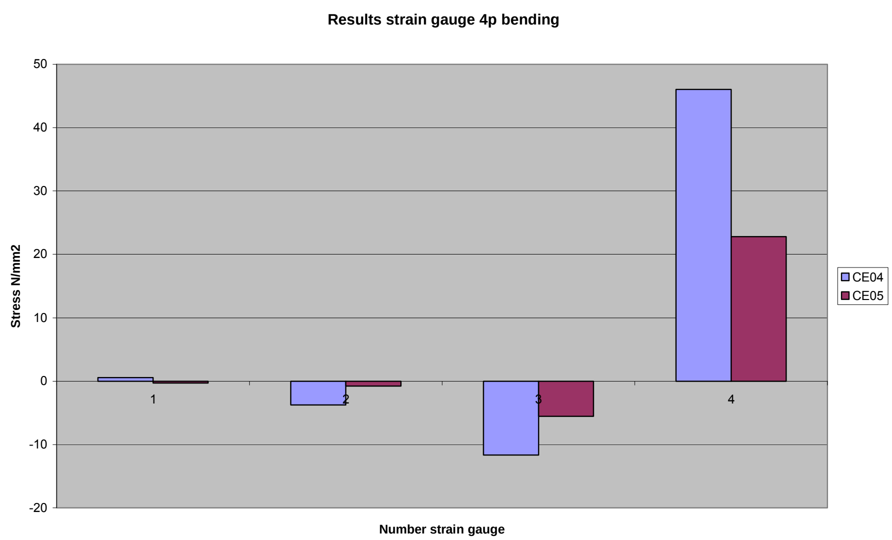
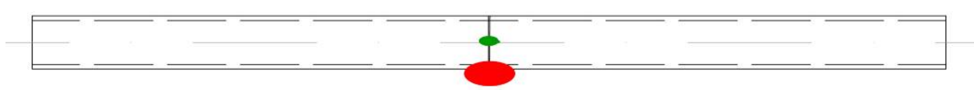


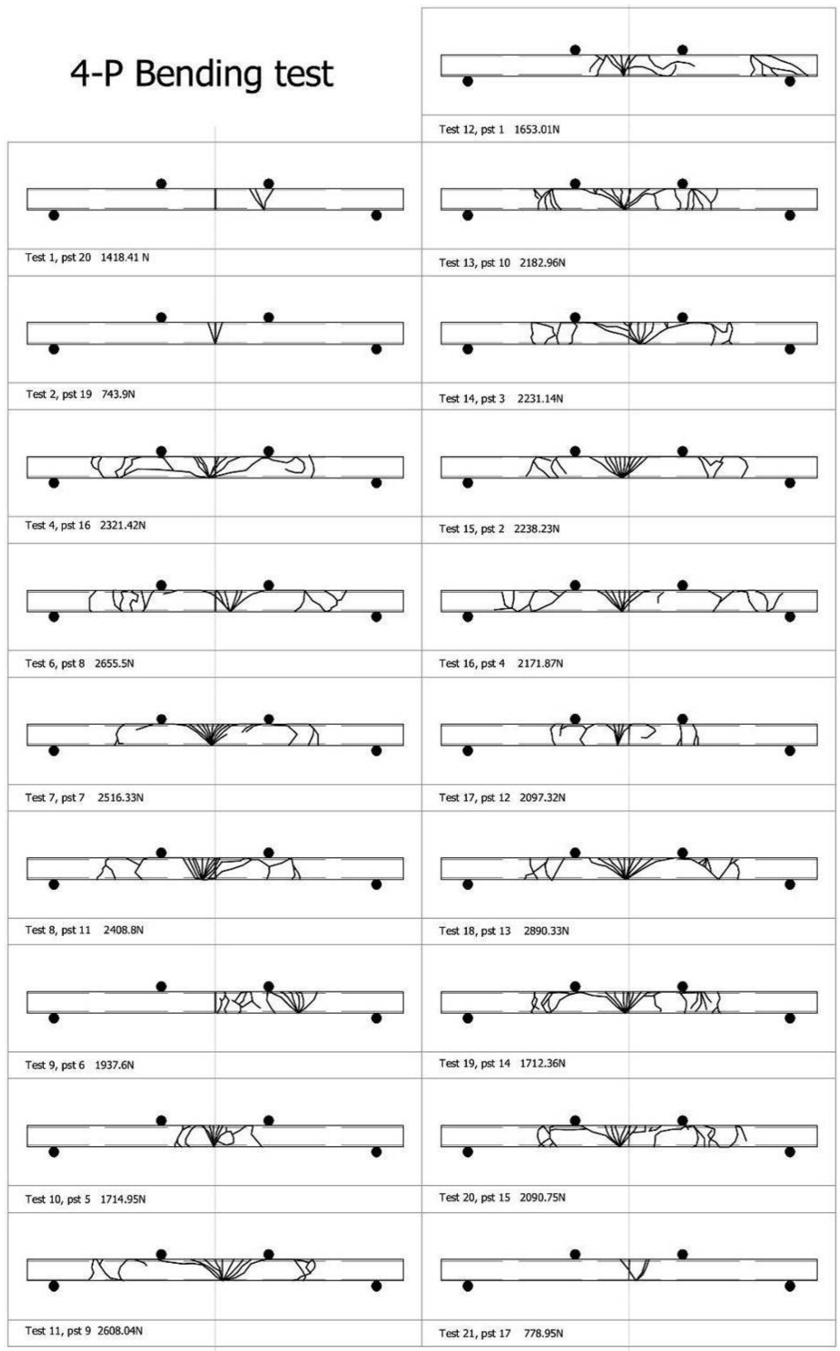
Figure 12.18 Stress as result of the strain gauges



12.10 Failure behaviour

The origin of fracture lies between the two force points, except in test 9. The fan shaped cracks start at the zone where the maximum tensile stress occurs. Higher failure forces show more cracks, due to the shock wave effect. The cracks form a path from the failure zone to the loading points, there it will hold up and than pursue their path down wards. Most specimen broke nearby the weld, but only test 2 and test 10 broke at the weld itself. Remarkably test 2 has a very low failure force. This could have been a production defect generated during the welding process, but could not be seen with the naked eye.

Figure 12.19 Failure mechanisms 4-point bending test



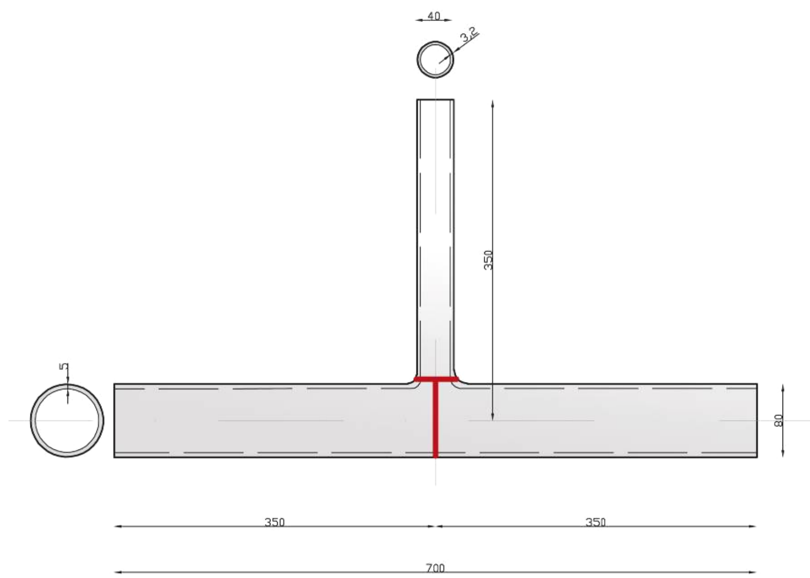
H13. Experimental research on butt welded t-joints

Compression test

13.1 Introduction

To define the strength of welded glass 9 glass t-joints are tested. The specimens are made out of two pieces of 350 mm glass tube and welded in the centre. These tubes have a diameter of 80 mm and a thickness of 5.0 mm. Perpendicular to this 80 mm tube, a glass tube of 350 mm, diameter of 40 mm and a thickness of 3,2 mm is welded.
The t-joint specimen will be tested with the help of a compression test. A compression test determines the behaviour of the glass under crushing load. On two specimen strain gauges are mounted, to measure the strain at certain points around the joint. All specimens were tested in a ZWICK Z010 and TestExpert software. This chapter describes the undertaken steps and the results of the compression test.

Figure 13.1 T-joint specimen compression test

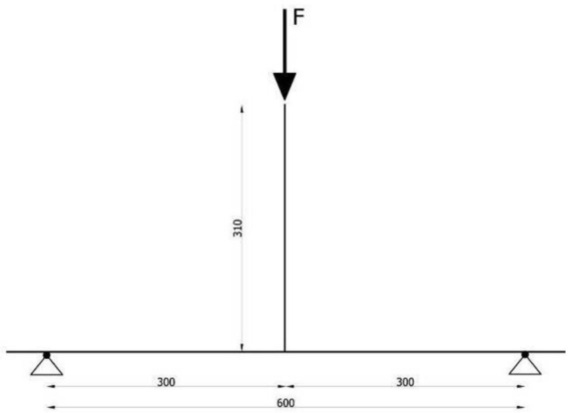


13.2 Diana input

To get insight into the stress distribution of tubes, the test setup is firstly generated in Diana. These results form the starting point of the input of the test rig and for analyzing the failure mechanisms and results from the strain gauges and tests. The next steps are undertaken in Diana. First the expected failure is calculated. It might fail on bending or on buckling.

13.2.1 Expected failure force bending:

Figure 13.2 Scheme Calculation T-joint



Assumption stress: σ ≈ 45 N/mm²

$$I_{tube80} = 832031\ mm^4$$
$$I_{tube40} = 63100\ mm^4$$
$$M_{max} = \tfrac{1}{2} F \cdot 300$$
$$\sigma_{max} = \frac{M \cdot z}{I}$$

F= 6240N

13.2.2 Expected failure force compression:

A rod under pressure stays straight as long as the compression force is smaller than the critical value (F_k). With the help of formula 11.6 the critical value can be calculated.

$$\sigma_{max} = \frac{F}{A}$$
$$F_k = \frac{\pi^2 EI}{L_k^2}$$
$$L_k = 2L$$

Pure pressure

F= 16650 N $<$ **F_k = 103687N**

13.2.3 Definition of the model geometry

With the help of the shape command, a normal cylinder, a truncated cylinder and four planes are created. By intersecting these shapes, surfaces are made and a 3d structure of the t-joint is defined. *The inserted load is a factor 10 smaller.*

Figure 13.3
Model geometry
Diana

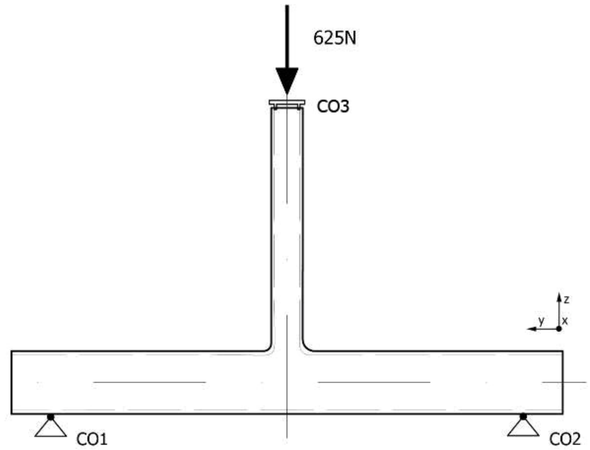
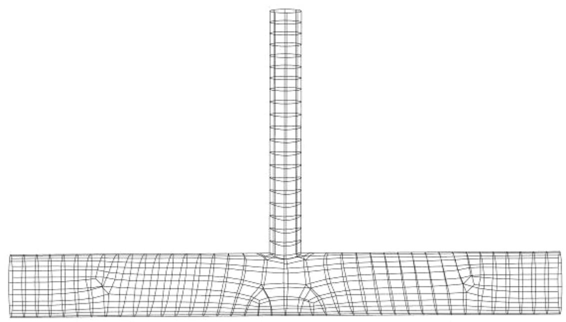


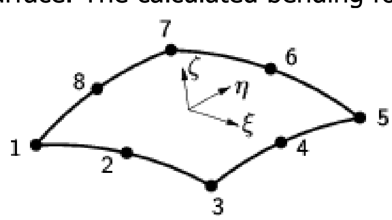
Figure 13.4
Created Mesh



13.2.4 Mesh and properties

The QU8 CQ40S element has 8 knots and is a curved shell element. This mesh is applied, because shell elements can accommodate forces perpendicular and parallel to its surface. The calculated bending force is normative.

Figure 13.5
CQ40S



Material properties	Young's modulus	64000 MPa
	Poisson's ratio	0.2
Physical properties	Thickness tube 80mm	5 mm
	Thickness tube 40mm	3.2 mm

Loads (pressure)	625N / 125mm (circumference) = 5 N/mm	
Constraints	CO1	X Y
	CO2	X Y
	CO3	X Z

13.2.5 Performing the analysis

The most important output from Diana are the principle stresses, but to understand the stress distribution completely, all stresses, membrane forces and bending moments are presented in a graphical way in appendix G . Hereunder the deflection, bearing force and principle stresses are illustrated.

Figure 13.6 Bearing stress x10

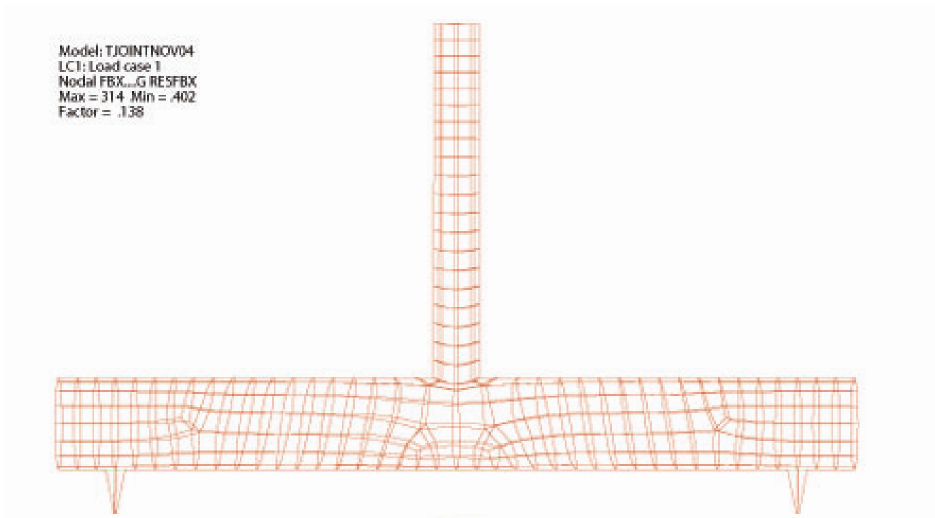


Figure 13.7 Deflection x10

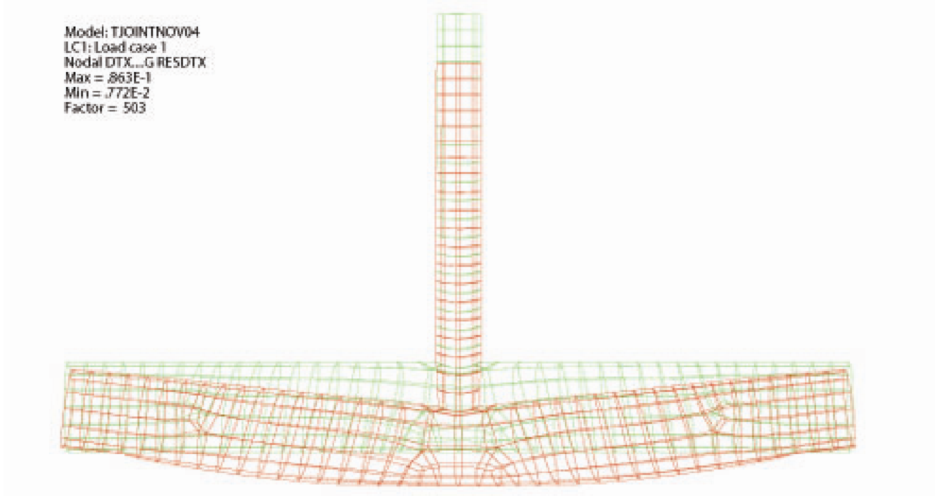


Figure 13.8
S1 principle
stress x10

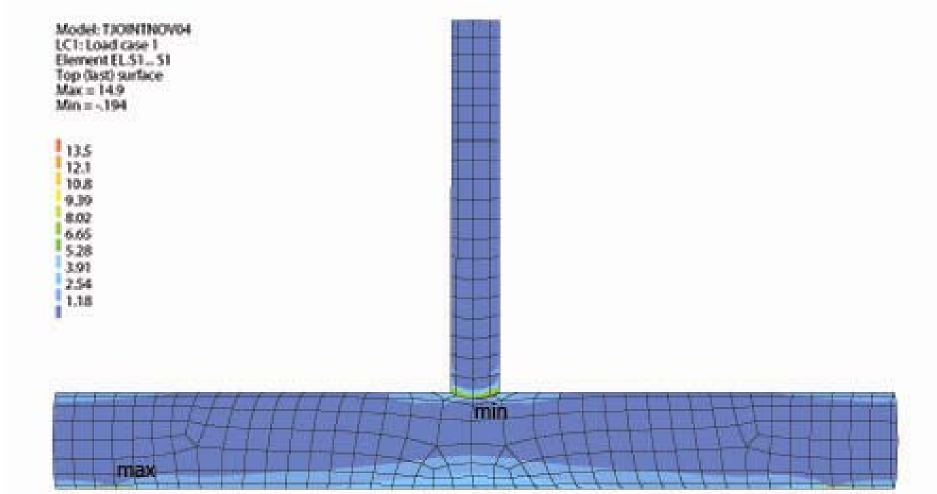
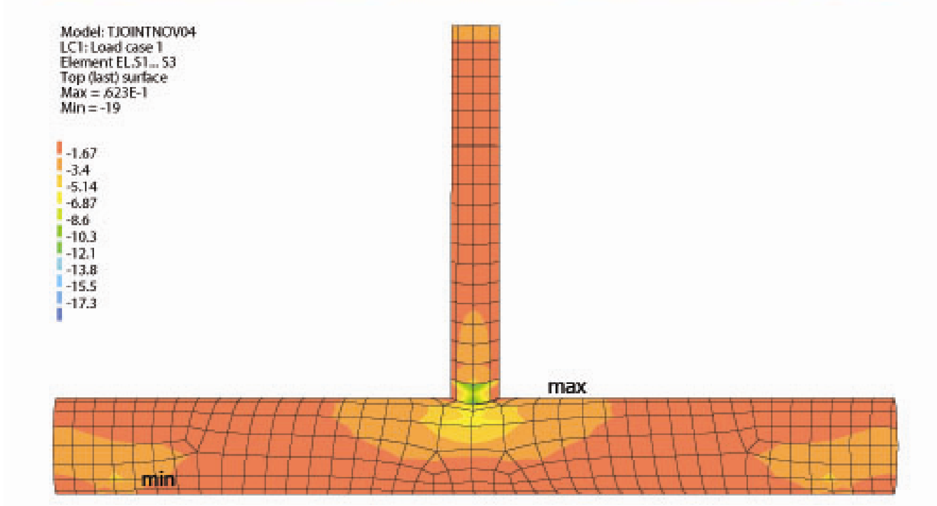


Figure 13.9
S3 principle
stress x10

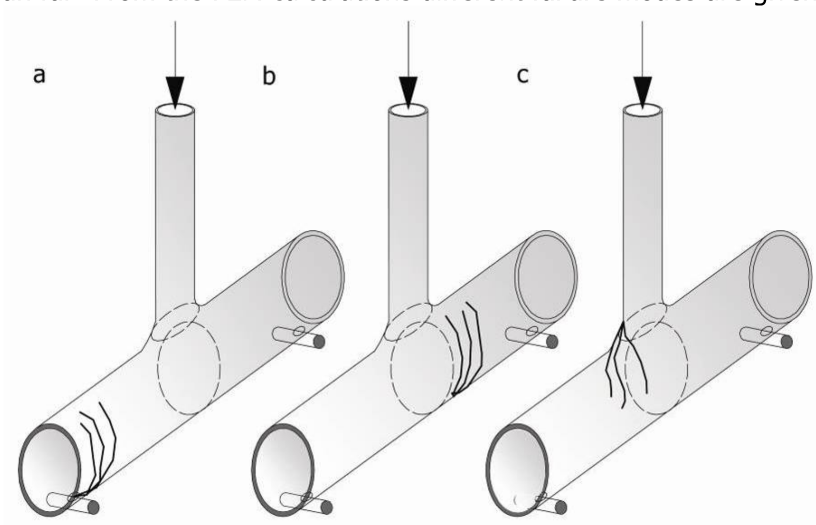


The stresses obtained from the FEM calculation are a factor 10 higher. The maximum tensile stress (s1) at the support is 149N/mm^2. The stress (s1) in the centre between the two support points is 34 N/mm^2.

13.3 Failure mechanisms

Glass fails under tension. Failure mechanisms describe the modes a specimen can fail. From the FEM calculations different failure modes are given.

Figure 13.10 Failure mechanisms compression test



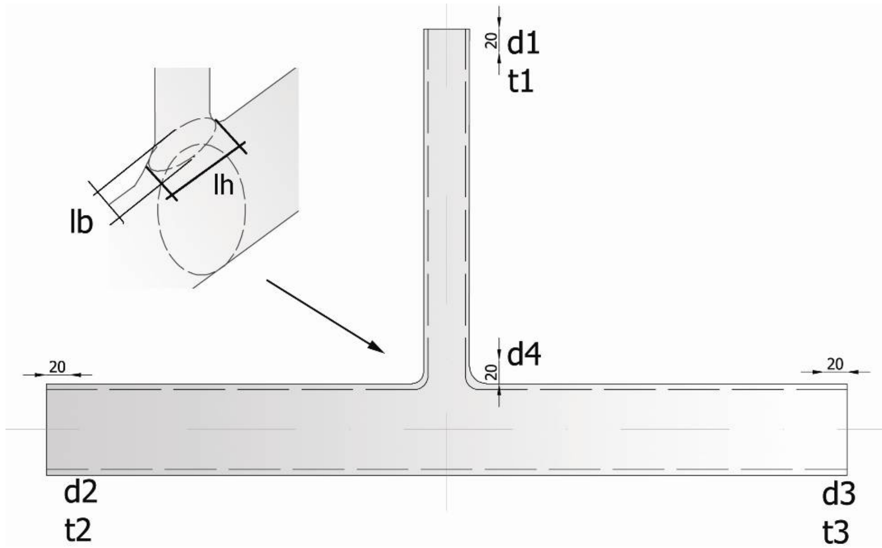
● Failure at the support. From the FEM-output can be read out that the highest stresses occur at the supports.
● Failure through bending. When calculating this test like a 3-point bending test, the highest moment lays in the middle of the main glass tube.
● Failure in the welded joint. The transition from 3.2 mm to 5 mm thickness of the tube might be a weak link.

13.4 Geometry inspection

The dimensions of the glass tubes, given in Figure 13.11 , are measured with a digital vernier calliper. To give an indication of the accurateness of the glass welding process, the proportions between the width and length of the joint are measured. A radius for the t-joint is not given to the manufacturer. After measuring the test objects all specimens were wrapped up in plastic to avoid glass splinters to fly while testing.

Because of the three dimensionality of the welded joint it is very difficult to measure the thicknesses. By means of pictures and AutoCAD, I attempt to analyze the sizes of the weld and the heat effected zones.

Figure 13.11 Measured places of the t-joint specimens



Compression	Average	Standard deviation%
$d_{outer(d2,d3)}$	80,21	0,25%
$d_{outer(d1,d4)}$	40,09	0,22%
A_p (mm^2)	1212,152	0,86%
I_p (mm^4)	858928	1,10%
HEZ (mm)	32,33	22%
L_h	58,78	3,40%
L_b	50,14	3,90%
L_h/L_b	1,17	3,30%

Table 13.1 Summary of the compression and moment specimens (except A_p and I_p maintube calculated values)

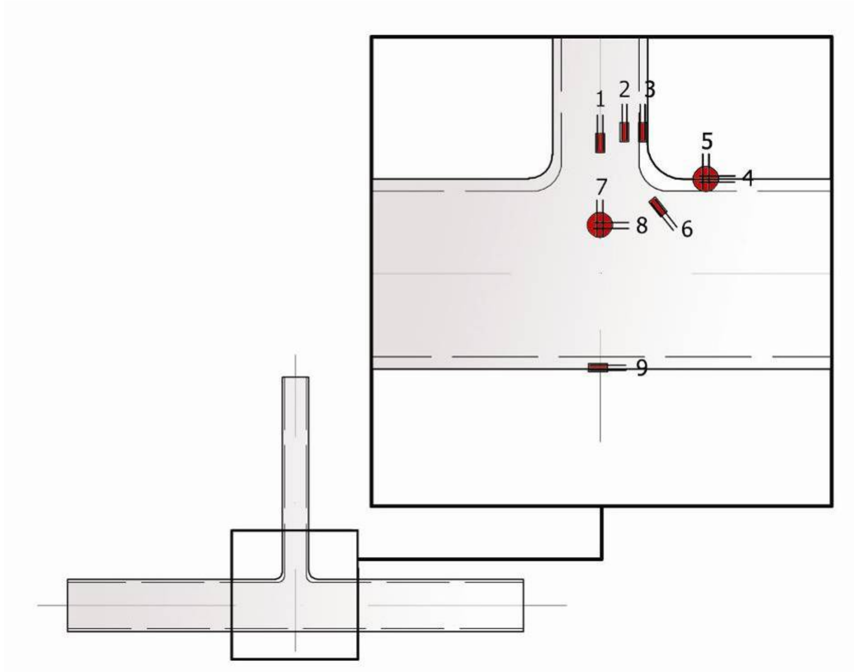
13.5 Strain gauges

Test object P1 and P2 were tested with strain gauges. The stress distribution is symmetric in crosswise and longitudinal direction, so that only 1/4 of the specimen is supplied with strain gauges. Axial to the force strain gauges 1, 2 and 3 are mounted. The remaining strain gauges are placed to give an indication on how the stress flows and how the glass tube will deform around the joint.

The gauge factors of the applied strain gauges are:

Single strain gauge:	2.10 1%	
Double strain gauge:		
Specimen P1:	1 : 2.07	1 : 2.07
Specimen P2:	1 : 2.12	2 : 2.12

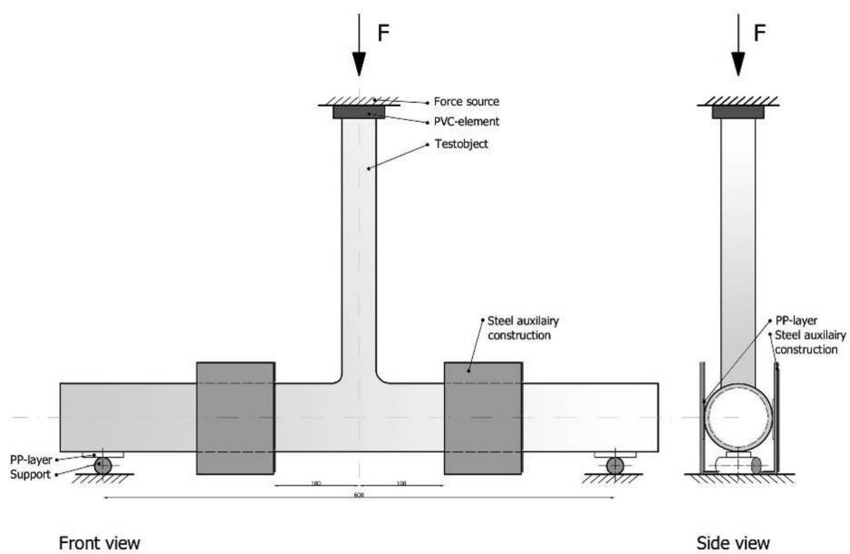
Figure 13.12
Strain gauges



13.6 Designing test setup

Because the t-joint is not a standard shape for material testing, the compression test is designed to fit in the t-joint into the ZWICK test rig. To transfer the load to the glass tube a PVC header with the tube's trace is placed at the top. To prevent side slipping of the main tube, an auxiliary construction is applied. Between the glass tube and the supports and the auxiliary construction PP slaps are mounted, to avoid direct contact with the steel test setup.

Figure 13.13
Design test setup



13.7 Testing

The under frame of the 4-point bending standard test rig is used and the support separation was manually set on 600mm. The auxiliary construction consists of two u-shaped elements and is mounted on the under frame. Each element is manually set on 100mm from the centre. A fixed compression head was installed and this force source is set in the centre, at 1/2 of the span. Before starting testing, data of the specimen and the test are inserted in the test program TestExpert. On the supports, the force source and between the auxiliary constructions polymers are placed to avoid direct contact with the steel. Tape is used to retain the glass tube from rolling.

First the glass tubes P1 and p2 are tested. These two are mounted with strain gauges. The displacement of the test rig is set on 0.25 mm/min and is slowly raised to 0.4mm/min. The goal of this test was to test the joint, but this test actually verifies the main tube. Therefore specimen #8 is tested with an extra support in the centre. This was a wrong interpretation of how to test the joint.

Figure 13.14
Test setup

13.8 Experimental results

13.8.1 Results of the compression test

The stresses are calculated like a 3-point bending test, assuming that the specimen fail where the maximum moment occurs. Most specimen show a strength above 50N/mm^2. The two tests (#1 and #2) with strain gauge show a lower strength than the others. Test #8 is not taken into account, because of the different way of testing. The finite element calculations where based on a force of 6250N, which resulted, according to Diana output, in a 34N/mm^2 stress in the middle of the main tube. The stress assumption was at the middle of the main tube was 45N/mm^2 and calculated as a 3 point bending test. The ratio between these values is 0.756. This results in more reliable stress derived from the FE-calculation in the middle of the main tube because the fillet distributes the force. However most specimen failed at the support. Derived from Diana output, where the maximum stress at the support is 149N/mm^2, the real stress at the support are calculated. The ratio between the FE stress in the middle, 34N/mm^2, and the analytical calculated stress is used to determine the stress at the support.

Zwick test	Test object	F (N)	M_{max} (N/mm)	$\sigma_{analytical}$ (N/mm^2)	$\sigma_{Fe,mid}$ (N/mm^2)	$\sigma_{Fe,support}$ (N/mm^2)
CE06 1	p2	4687,43	1406229	32.63	24.65	108.04
CE07 2	p1	6344,82	1903446	44.56	33.67	147.54
3	p3	7364,92	2209476	52.63	19.76	174.26
4	p4	8127,34	2438202	56.9	42.99	188.40
5	p5	7453,38	2236014	52.36	39.56	173.37
6	p6	7628,3	2288490	53.45	40.38	176.98
7	p7	6657,81	1997343	46.51	35.14	154.00
*8**	*p8*	*2026,9*	*608070*	*14.22*	*10.74*	*47.08*
9	p9	9060,34	2718102	62.41	47.15	206.65

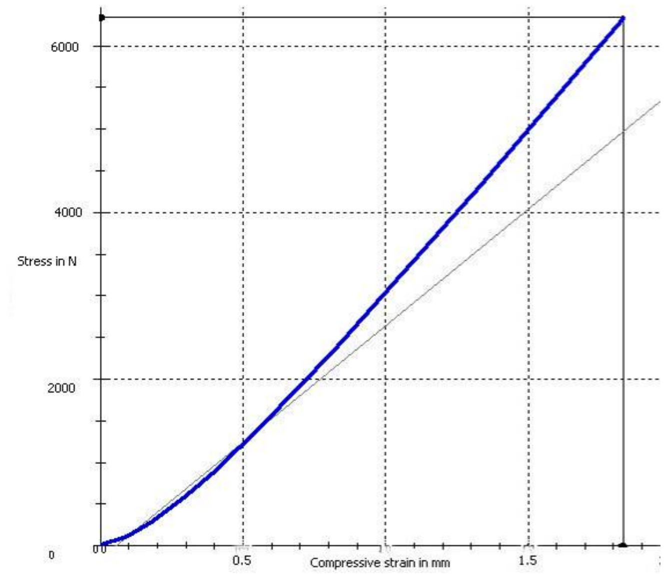
Table 13.2 Results compression test

	F{lo max} N	$\sigma_{analytical}$(N/mm^2)
Average	7165,54	50.19
SD	1305,18	9.02
SD%	18%	18%

Table 13.3 Summarized results of the compression test

The graph line shows a linear elastic curve. Because glass does not demonstrate plastic behaviour is this graph typical glass behaviour related. In the beginning the graph diverge slightly form the linearity. This can be explained by the use of the polymer at the support that leads to setting of the specimen within the auxiliary construction.

Figure 13.15 Graph compression test, test #2



13.8.2 Results strain gauges

Markedly are the small tensile stresses at #3. The material is probably that stiff so when the force is transmitted by the joint to the main tube, this results in a very small tensile stress. This test does not actually verify the joint, but tests the main tube. That is why the highest tensile stresses obtained from these strain gauges occur in the centre of the main tube. The calculated values in the centre of the main tube are respectively 32.36N/mm^2 and 44.56N/mm^2. The strain gauge #9 is mounted at that place and gives a stress of respectively 27N/mm^2 and 37N/mm^2. However none of the specimen failed at the point where the strain gauge is mounted (see Figure 13.18). The highest stress occurred at the support.

Figure 13.16 Strain gauge results compression test

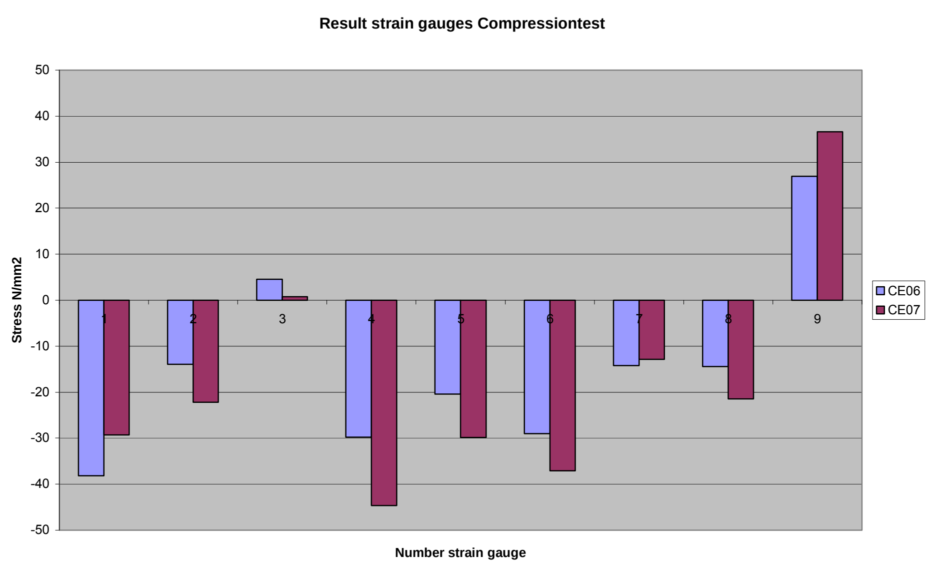
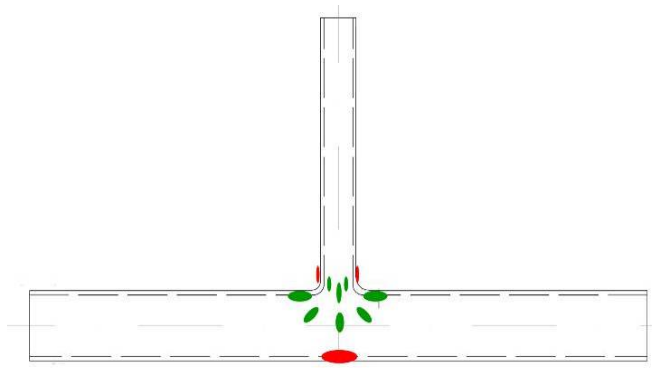


Figure 13.17
Stress distribution

red: tensile

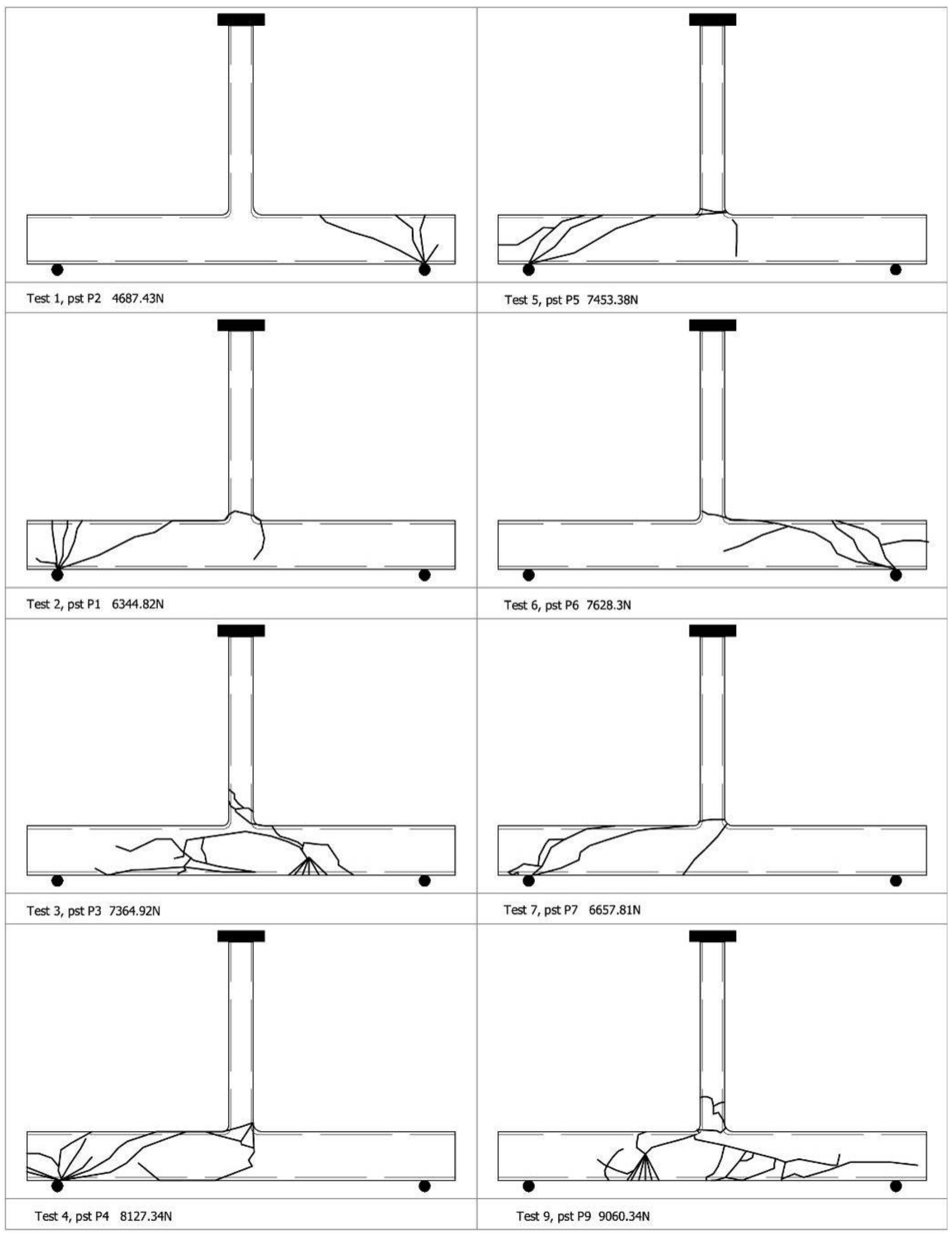
green: compression



13.9 Failure Behaviour

Six of the eight specimens failed at the support. Stress peaks occur due to the small support area of the tube. Due to the form in position of the joint, the force is diffused regularly through the main tube. This test does not actually test the joint, but tests the main tube. This test should have designed differently, so that the main tube is fully supported and not only on two supports. All specimens showed abrupt failure and their cracks run their path to the joint.

Figure 13.18
Crack patterns



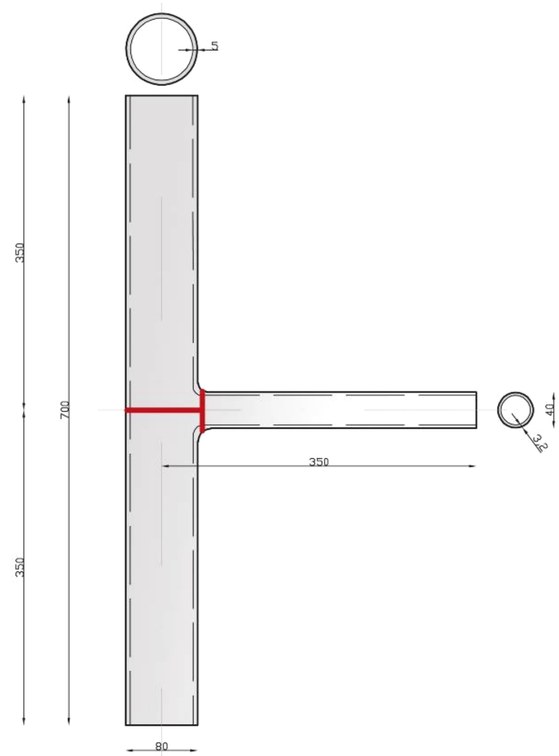
H14. Experimental research on butt welded t-joints

Moment test

14.1 Introduction

To define the strength of welded glass 10 glass t-joints are tested. The specimens are made out of two pieces of 350 mm glass tube and welded in the centre. These tubes have a diameter of 80 mm and a thickness of 5.0 mm. Perpendicular to this 80 mm tube, a glass tube of 350 mm, diameter of 40 mm and a thickness of 3,2 mm is welded. The t-joint specimen will be tested with the help of a moment test. With this test it is possible test the behaviour of the welded joint when subjected to a moment. The maximum moment arises where the two glass tubes interfere. Also in this experiment two specimen are mounted with strain gauges. This chapter describes the undertaken steps and the results of the moment test. All specimens were tested in a ZWICK Z010 and TestExpert software.

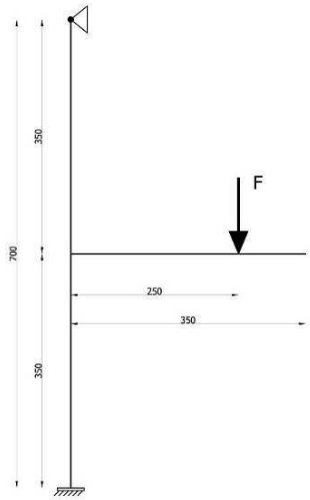
Figure 14.1 Geometry of specimen



14.2 Diana Input

The T-joint is modelled in Diana to calculate the stress distribution in the joint. First the expected failure force is calculated.

Figure 14.2 Scheme Calculation T-joint



Expected failure force bending:

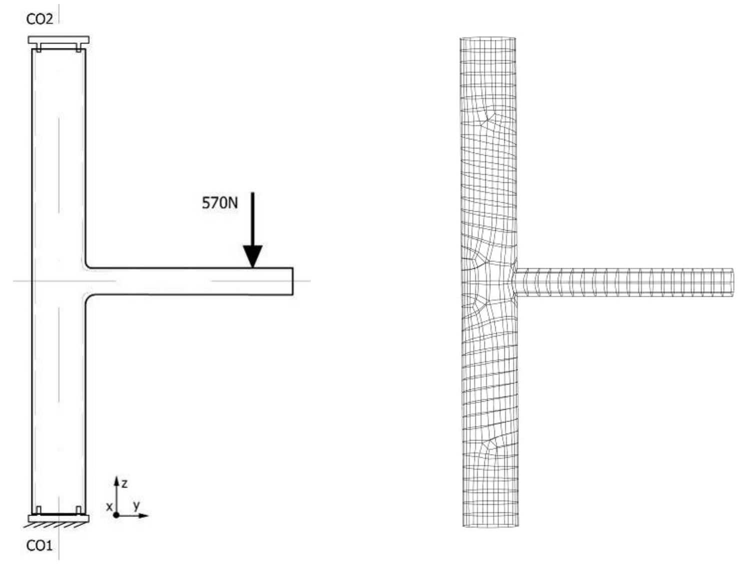
$$I_{tube80} = 832031 \ mm^4$$
$$I_{tube40} = 63100 \ mm^4$$
$$M_{\max} = 250F$$
$$\sigma_{\max} = \frac{M \cdot z}{I}$$

F= 567.9 N

14.2.2 Definition of the model geometry

With the help of the shape command, a normal cylinder, a truncated cylinder and four planes are created. By intersecting these shapes, surfaces are made to define the t-joint.

Figure 14.3 Scheme Calculation T-joint



14.2.3 Mesh and properties

The QU8 CQ40S element has 8 knots and is a curved shell element. This mesh is applied, because shell elements can accommodate forces perpendicular and parallel to its surface.

Material properties	Young's modulus	64000 MPa
	Poisson's ratio	0.2
	Thickness tube 80mm	5 mm
Physical properties	Thickness tube 40mm	3.2 mm
Loads (force)	570N	
Constraints	CO1	XYZ
	CO2	XY

14.2.4 Diana Output

The hereunder presented output form the basis for further analyze before and after testing. See also appendix G.

Figure 14.4
Bearing stress

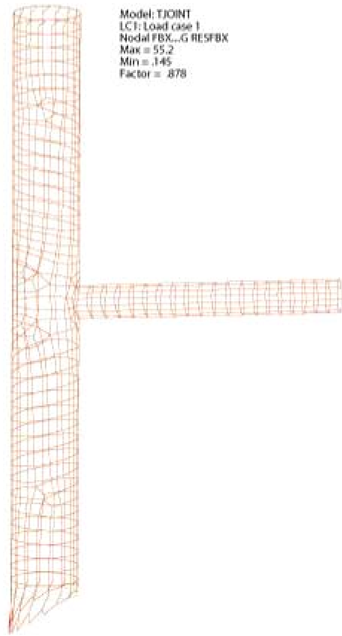


Figure 14.5
Deflection

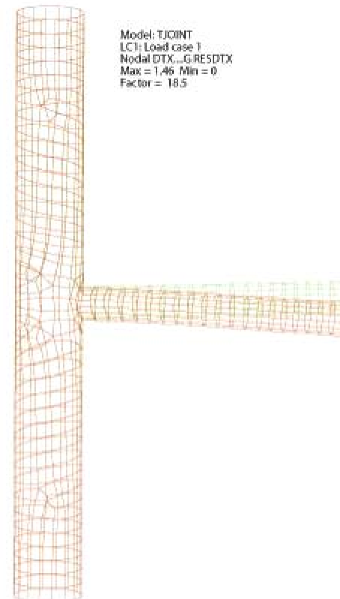


Figure 14.6
Principle stress S1

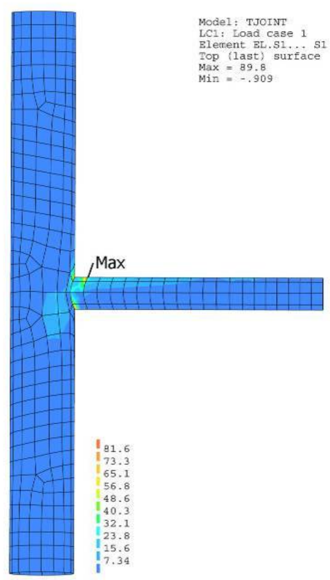
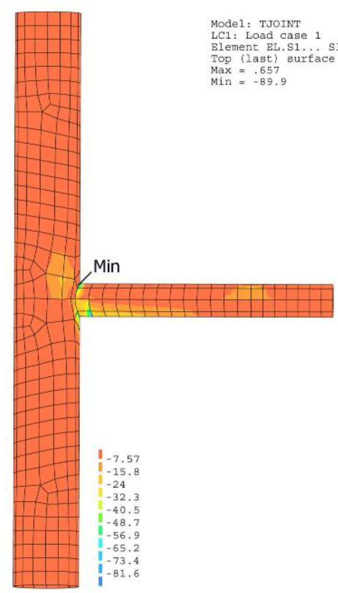


Figure 14.7
Principle stress S3



14.3 Failure mechanism

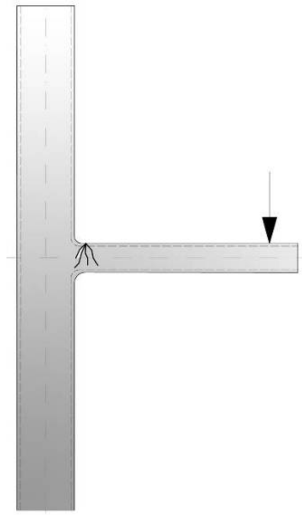


Figure 14.8 Failure mechanism

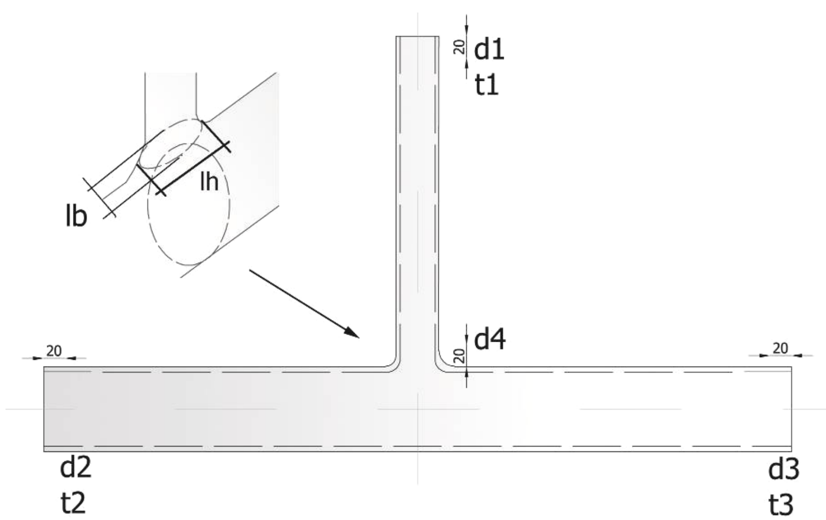
To understand the effect of the maximum stresses on a body, it is necessary to describe the failure mechanisms. These will give better insight into the behaviour of glass tubes subjected to this moment test. When looking at the FEM calculations the expected failure mechanism will be just in front of the joint.

14.4 Geometry inspection

The dimensions of the glass tubes, given in Figure 14.9 are measured with a digital vernier caliper. The proportions between the width and length of the joint are measured, to give an indication of the accurateness of the glass welding process. After measuring the test objects all specimens were wrapped up in plastic to avoid glass splinters to fly when testing.

Because of the three dimensionality of the welded joint it is very difficult to measure the thicknesses. By means of pictures and AutoCAD, I attempt to analyze the measurements of the weld and the heat effected zones.

Figure 14.9 Measured places of the t-joint specimen



Moment	Average	Standard deviation%
$d_{outer(d2,d3)}$	80,21	0,25%
$d_{outer(d1,d4)}$	40,09	0,22%
A_m (mm^2)	374,2282	0,91%
I_m (mm^4)	64208,91	0,78%
HEZ (mm)	32,33	22%
L_h	58,78	3,40%
L_b	50,14	3,90%
L_h/L_b	1,17	3,30%

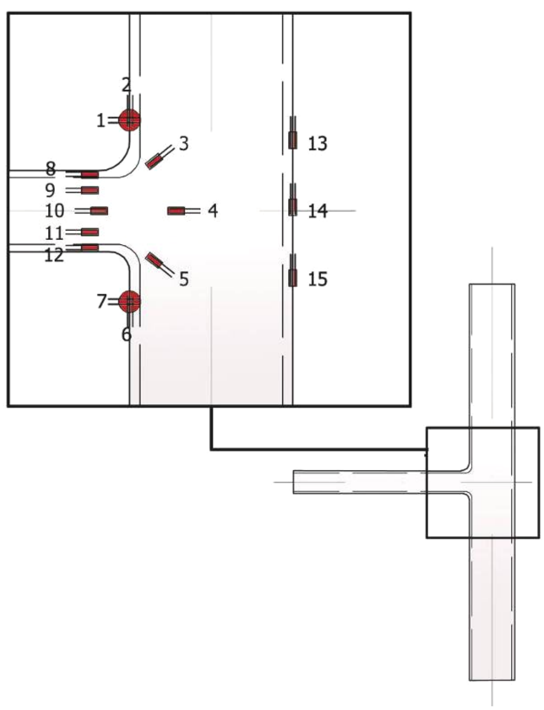
Table 14.1 Summary of the compression and moment specimen(except A_m and I_m small tube calculated values)

14.5 Strain gauges

Test object M1(Ce03) and M2(Ce02) were tested with strain gauges. In this test the stress distribution is symmetric in longitudinal direction, so that only 1/2 of the specimen is supplied with strain gauges.

Two double strain gauges were used to measure the strain at the top and bottom of the joint. With the help of the single strain gauges, that are fan-shaped mounted on the joint, it will give a good indication on how this type of joint reacts on the moment.
The gauge factors van of the strain gauges are:
Single strain gauge: 2.10 1%
Double strain gauge: 1 : 2.12 2 : 2.12

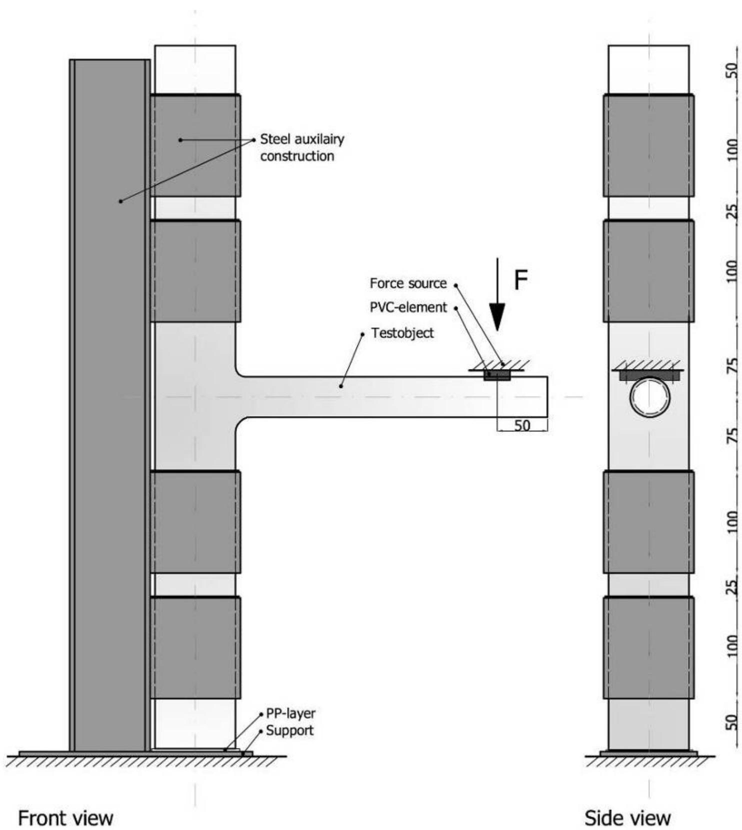
Figure 14.10 Mounted strain gauges



14.6 Designing test setup

Because the t-joint is not a standard element for material testing, the compression test is designed to fit in the t-joint into the ZWICK test rig. An auxiliary construction is applied to clamp the main tube. It is made out of a steel h-profile, so it is stiff enough to avoid bending and to ensure that the t-joint will be subjected to a moment. The auxiliary construction is mounted on the standard 4-pointbending under frame. The force point, the upper part of the 4point bending test rig, is supplied with a PVC block with the tube's curvature and is set at 250mm from the joint, 50mm from end of the arm. Between the steel frame and the glass t-joint pp-layers are slid, to avoid direct contact with the steel.

Figure 14.11 Design test setup



14.7 Testing

The H-profile is placed at the end of the under frame of the 4-point bending test. On the force source the pvc-element is assembled and is manually fixed at 50mm of the end of the glass tube. The force source is fixed to avoid slipping. Before starting testing, data of the specimen and the test are inserted in the test program TestExpert.

First the glass tubes M1 and M2 are tested. These are mounted with strain gauges. The strain gauges are connected to the amplifier. The displacement of the test rig is set on 0.5mm/min and after two test raised up to 0.8 mm/min.

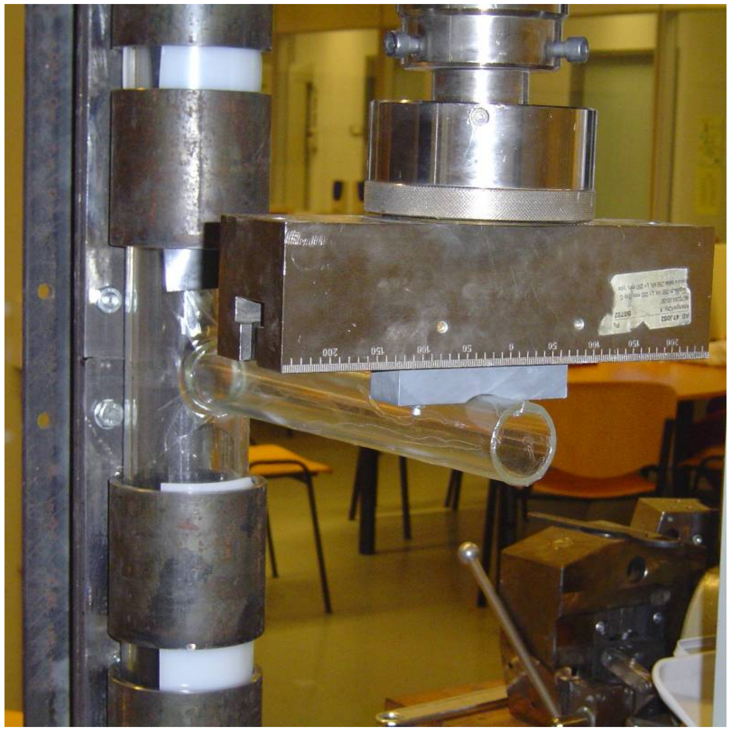


Figure 14.12 Test setup moment test

14.8 Experimental results

14.8.1 Results of the moment test

The results from this test have a much smaller spread than the 4-point bending and compression test. They show a failure force within a small range. The strength is slightly higher than the strength obtained from the 4-point bending test. Also in this test, the tested tubes mounted with strain gauges have lower strengths. The stress at fracture spot derived from FE-analyses is 84N/mm^2. The inserted force in Diana is based on 45N/mm^2. The ratio between this stress and the analytical calculated stress is used to convert the stress of 84N/mm^2. The finite element method calculated failure stress is listed in 0.This large difference can be explained by the model in Diana. The fillet of the joint was not modelled and this leads to a right angle between the arm an the main tube. The stress distribution merges not gradually, so stresses raises.

Zwick test	Test object	F(N)	M_{max}	σ_{max}(N/mm^2)	$\sigma_{Fe,max}$(N/mm^2)
1	m2	-	-	-	
Ce02 2	m2	699,98	174995	54,90	102.5
Ce03 3	m1	841,14	210285	66,15	123.5
4	m4	964,4	241100	74,09	138.3
5	m3	933,23	233307,5	73,28	136.8
6	m5	1087,12	271780	85,31	159.2
7	m6	928,1	232025	72,06	134.5
8	m7	904,6	226150	70,42	131.5
9	m8	1035,01	258752,5	81,12	151.4
10	m9	921,46	230365	71,70	133.8
11	m10	900,71	225177,5	70,87	132.3

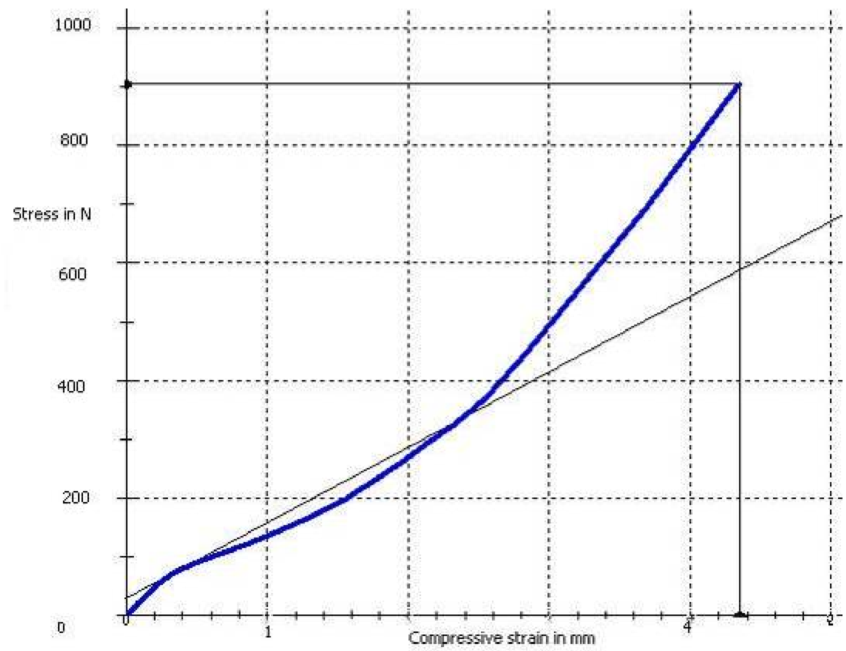
Table 14.2 Results of the moment test

	F{lo max} N	$\sigma_{max}(N/mm^2)$
Average	921,58	71,99
SD	104,66	8,14
SD%	11%	11%

Table 14.3 Summarized results of the moment test

This graph also shows a linear elastic curve. The first half of the curve's tendency is showing a s-shaped start. This is because of the test setup. The main tube could not perfectly be clamped and the pvc force source could entail some movement.

Figure 14.13 Graph moment test, test #8



14.8.2 *Results strain gauges*

Stresses in position of the strain gauges can be calculated by: ($E=64000N/mm^2$)

$$\sigma = E\varepsilon \qquad (14.1)$$

The tensile stresses are located on the top of the small tube and at the top connection to the main tube. The highest stress appears to be at #8. This is also the place where all specimen fail. From 0the stress is respectively $54.9N/mm^2$ and $66.15N/mm^2$. The results from the strain gauges #8 are respectively $33N/mm^2$ and $60N/mm^2$. Between 54.9 N/mm^2 and 32 N/mm^2 lies a big difference. An explanation for this is that strain gauge #8 from the CE02 series was not mounted properly. The gauge #4 and #14 is placed in the neutral line and show a small tensile stress. Strain gauge #10 is also placed in the neutral line, but because of the manual attachment of the gauge a difference occurred in tensile and compression.

Figure 14.14 Comparison of the strain gauge results

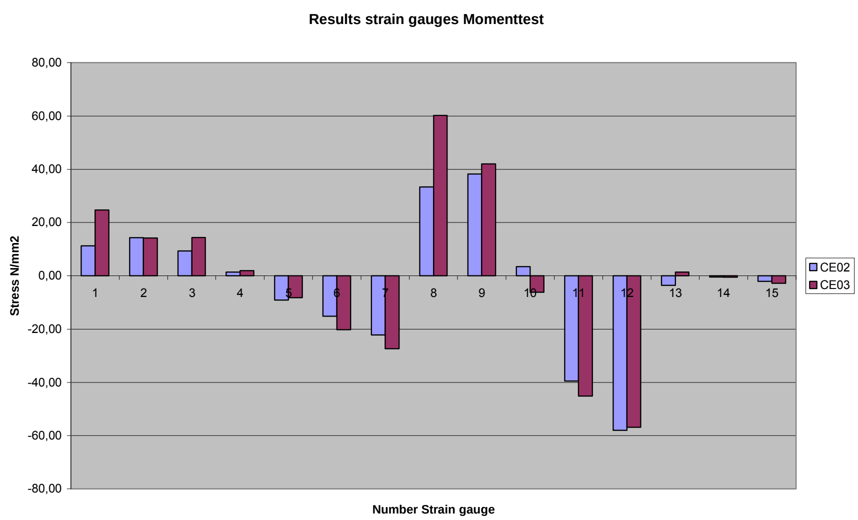
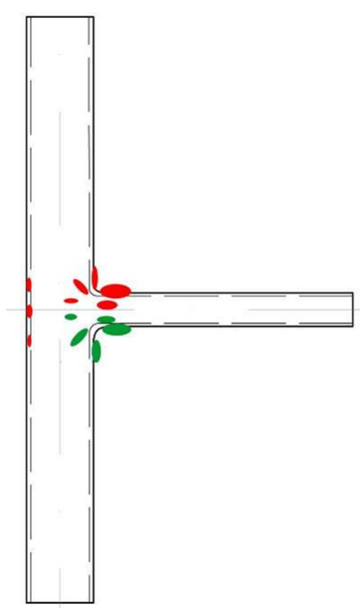


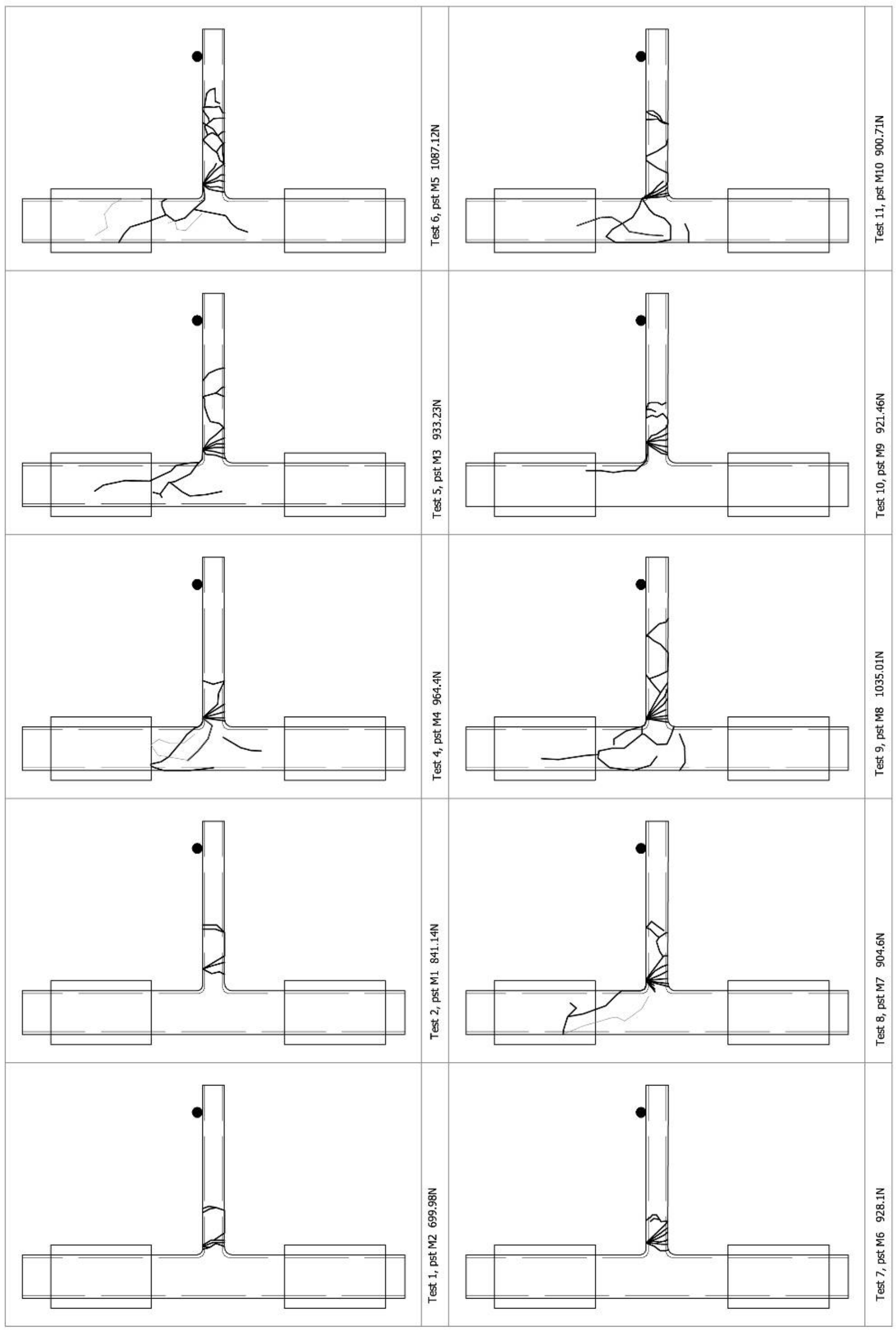
Figure 14.15 Stress as result of the strain gauges. Red for tension and green for compression stress



14.9 Failure Behaviour

Every specimen showed abrupt failure. The crack pattern principle is in every specimen the same. There is no obvious preference for the welded joint or heat effected zone. Only at the last test failure occurred in the weld, but the failure force is not significant lower than in the other tests. All cracks start at the tensile zone and follow there path in a fan-shaped course downwards. Due to shock wave effect the crack follow their path upwards to 1/3 of the span. Shock waves are characterized by an abrupt change in the characteristics of an object. Larger shock waves occur when a greater force is applied. Specimen failing at a force higher than 1kN show more cracks.

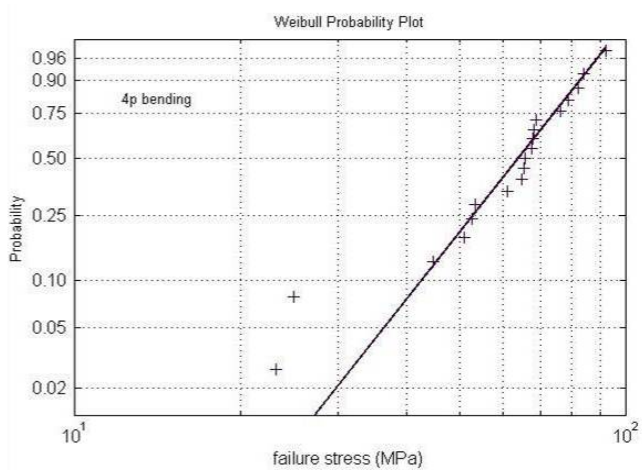
Figure 14.16 Failure mechanisms



H15. Statistical Analyse

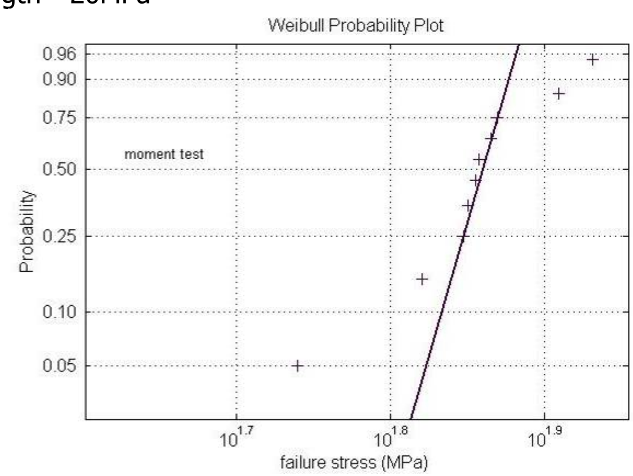
Many international standards exist for the determination of glass thicknesses and the type of glass required for a certain load case.[1] At this moment no standards exist for borosilicate glass tubes. To predict the failure of this type of glass, the results of the tests are plotted in a Weibull distribution. The stresses calculated by the failure force and the geometry of the tube are plotted in the graphs hereunder.

Figure 15.1 Weibull plot 4-point bending test



Design strength ~20MPa

Figure 15.2 Weibull plot moment bending test



Design strength ~ 65MPa

Using the Weibull distribution can not be done in every case[2], because not all values follow the Weibull line quite well. These test follow the Weibull plot quite well, but in the 4-point bending and moment test the two lowest values do not fit. The middle values of the moment test a clustered together and follow the Weibull plot quite reasonable. Remarkably is that the two test objects with strain gauges from every test give a lower strength. These

[1] The institution of Structural Engineers Structural (1999), Structural use of glass in Buildings, London.

[2] Veer, F.A. Louter, C. Romein, T. Quality control and strength of glass, Delft

specimens are transported and touched more often. This might not directly be a linked with another.

The American Code charts are based on a probability of failure under design load of 8/1000.[1] This is valid for annealed float glass panes, but almost 1% probability for structural glass might be to high. The failure probability represents the y-axis of the Weibull graph. When reading out y=0, the 4-point bending test will give a design strength of $10^{1.28}$ which corresponds to a strength of 20MPa.

The bending moment diagram of the compression test is schematically drawn as a 3-point bending test. The maximum moment lies therefore in the centre of the main tube for calculating the maximum stress. None of the tubes failed at this point, but most of them failed at the support. According to DIANA output, the maximum tensile stress lies at the support. This means that the actual failure stress is higher than calculated in the analytical way. In 0the stress at the support is presented to give an indication of the failure stress.

The design strength if the moment test is much higher than the results obtained from the 4-point bending test ($10^{1.82}$~65N/mm^2) . All test objects fail at approximately the same point. This is the transmission zone from the main tube, with a thickness of 5mm, and the arm, with at thickness of 3,2mm. These thickness difference could lead to an unequal distribution of the glass thickness and results in a difference in moment of inertia. A higher tube thickness results in a higher moment of inertia and calculating the stress with a higher moment of inertia, results is a smaller stress. Most specimen did not fail at the 250mm span, but a few centimetres before the welt. When the span becomes smaller, the moment drops too (M=Force x arm). This lead to a lower stress at failure.

Another explanation for the great spread in strength is the amount of tested specimen. In the 4-point bending test 19 specimen are tested, in contradiction to 8 specimen in the compression test and 10 objects in the moment test. A large amount of objects that can be tested will result in a smaller distribution in design strength and results to a design strength that approaches the real strength the best. Within this research it was not possible to perform that many tests, due to costs and time.

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1 The institution of Structural Engineers Structural (1999), Structural use of glass in Buildings, London. SETO

H16. Conclusions

Opportunities for the application of welded glass in the building industry are there. The possibilities with regard to shaping are quite great and can therefore give new design possibilities to architects . However flat glass is no option yet and the sizes are limited (till ~2m) because of the size of the annealing furnace.

The welded joint is not by definition weaker than untreated glass tubes.

The geometrical properties of the borosilicate glass tubes are quite constant. The coefficients of variation of the diameter and areas are below 1.5 percent. The size of the heat effected zone is on the contrary quite variable and the coefficient of variation of the rate between the height and the width of the joint stays under 3.5%.

Failure of welded glass is not by definition at the welded or heat effected zone.

There is no relation between the heat effected zone and the failure force and between the height or width of the joint and the failure force.

H17. Recommendations

This research has proven that the application of welded glass in the building industry is possible. Because of the initial stage of this application, more research needs to be done. For the next points further research is definitely recommended:

1. Because of the absence of standards for the calculation and design guidelines of structural glass safety should be guaranteed. Therefore research about improving the safety within the welded elements needs to been done. The possibilities and ways of lamination and strengthening of shaped welded glass. By performing test could be find out the failure behaviour and the (initial) strengths.
2. The effect on the welded joint with the application of pre-stressed cables running through the glass tubes needs to be researched.
3. The complete calculation of the structure has not be done. Because of the application of a pretty complex three dimensional structure and pre-stressing the task is too time-consuming. To obtain a good calculation more knowledge about the FEM DIANA computer program is necessary. Further research also needs to be done to the stability of this kind of the structure.
4. Constructive analyse of the joints in chapter H9. The developed joints needs to be examined on the force distribution and the deformations.
5. The development of a moving annealing furnace could give a solution for the limited sizes.
6. The radius of the t-joint was not given to the manufacturer. The use of a moult to obtain exactly the same welded joint, result is more accurate values.
7. Performing the test with the help of a polarizer. The colours that appear, when looking through the polarizer while testing, can give a three dimensional representation of the stress distribution.
8. To obtain the real stresses at the failure zone, all specimen tube thicknesses should have been measured at the initial crack after testing. Calculating with the real thicknesses and the distance between the force load and failure zone would lead to a more accurate design strength.
9. Because of the cylindrical shape of a tube it is hard to determine the homogeneity of the wall thickness. The wall thickness at the t-joint could not be measured with the help of pictures and AutoCAD. A solution for this must be found.
10. For the compression test a settle support could avoid peak stresses at the support. To test the welded joint it was even better to use line support.

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http://vision2form.nl

Compagnies

Leidse Instrumentmakers school, Leiden. Mr. Van As and Mr. Frans Volst
Louwers Glastechniek, Hapert. Mr. Bert Schepers
Schott Glass. Mr Martijn Kok
QVF Engineering GmbH. Mr. Hendrik Baukens

Appendices

Appendix A LIS, Leiden

November 28th, 2006
Mr. van As

Leidse Instrumentmakers School was founded by Prof. dr. Heike Kamerlingh Onnes in 1901. It is a MBO school specialized in fine mechanics and precision industry.
Practice specialisations are:
- Metal
- Glass
- Optics
- Mechatronica
- Laser technology

The glass blowing department is a supporting service of the University of Leiden. The laboratory ware that is made, is used for scientific research.

I was invited to pass a day with the glass blowing class. However the scale of the products are so much smaller that the scale of a building element, it gave me a better insight into the possibilities of glass and a better feeling of how glass reacts to temperature differences.

I even got the possibility to try it myself. The standard tube length is 1500mm. To get a workable tube it needed to be cut. A glass tube is easy to cut. To get a clean edge one single sharp scratch is enough to break it. First I had to try to make a sidebar and later small bubbles with two sidebars. To start the right flame size for heating up the soda-lime glass tube should be determined. It is important to keep on rotating the tube while keeping it in the flame. Meanwhile the tube is held horizontal otherwise the surface will not be heated equally. When the glass got viscous enough it was possible to transform the tube. When taking it out of the flame it was possible to turn and pull the glass tube into little bubbles with two promontories. To determine if the glass is soft enough it is just a question of feeling and can't be learned in one day. So after doing this several times, balls could be made out of the bubbles. One of the sidebars should be transformed into a butt joint, so a closed bubble was made. After heating the bubble again it was possible to blow though the other sidebar so I could make a ball. During this whole process, rotating the glass object should be maintained. Otherwise the glass would sag under its own weight. When working with soda-lime glass the glass should be heated very slowly. It is not that resistant to thermal shock and I experienced that too. A few times my glass object exploded.
It is also possible to work with different kinds of glass, borosilicate glass and quartz glass. For heating these glass types other torches were used. Because these glasses have a higher softening point, a warmer flame is needed. When holding quartz glass in a flame a very small but intense white light is visible, but with soda-lime and borosilicate glass only the flame became a little bit more intense. Manually they reach to make objects exact to 0.01mm. After the glass objects are finished they are put in a furnace for 3 hour at a temperature of 540ºC and than cooled down slowly.

Figure 1
Turning in the flame

Figure 2
Bubbles with sidebars

Figure 3
Glass blowing

Figure 4
Welding in a lathe

Figure 5
The Annealing oven

Appendix B Flat vs Tube glass

Flat glass	**Tube glass**
Stability	
A flat pane is stable when lying, but while standing it isn't stable. Stability can be achieved by bending flat glass or by putting a pane perpendicular to the other one.	A tube is the best shape with regard to buckling and torsion. This is because of its moment of inertia. It is the same in every direction of the section**.**
Safety	
Flat glass can be strengthened (borosilicate glass not fully) and laminated with a PVB foil. But after these interventions it is difficult to deform or work it.	It is possible to strengthen glass tubes, but this is not an easy process. However in the glass welding industry many forms are made and probably a double skin can be made. In this cavity it might be possible to put a resin.
Feasibility	
Welding of flat glass is not a common action. When welding flat glass the entire final product must be preheated in an oven and while still warm it can be welded. The largest elements that have been made are ~400x400mm and the thickness is limited to 10mm.	The glass welding industry is mostly focussed on tubular structures. The facilities are attuned to these forms. The tubular form is easier to heat and weld in a lathe. Besides more form freedom is possible.

Appendix C Scale model

Figure 1 Working drawing scale models

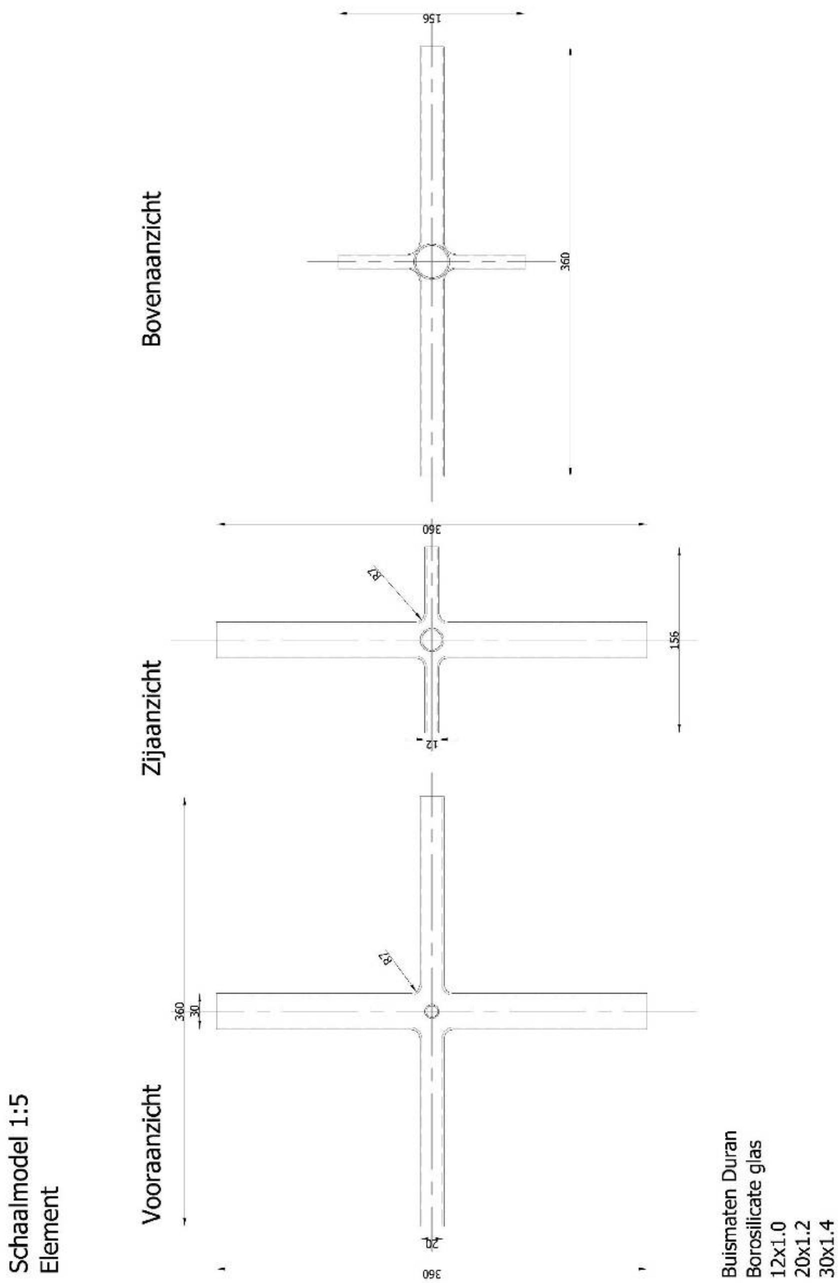
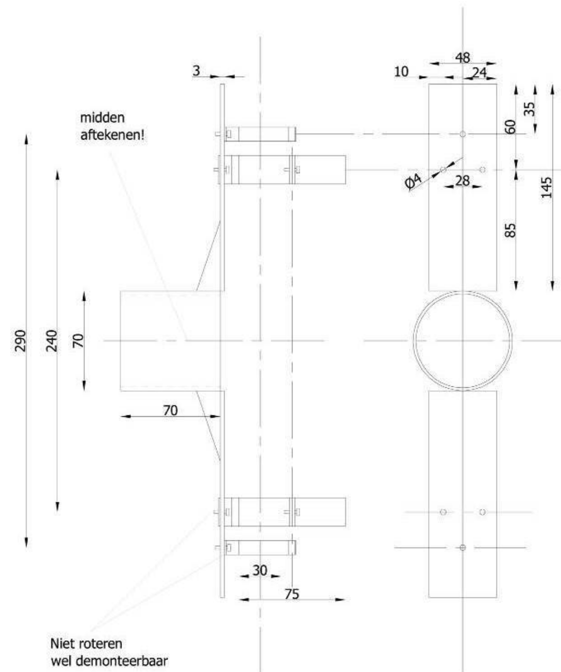


Figure 2 Working drawing, auxiliary construction for welding the scale models, side view and front view



Appendix D Flowchart

Flowchart calculation sheet according to NEN6702:2007

Veiligheidsklasse en referentieperiode in jaren
Veiligheidklasse 3
Referentieperiode 50jaar

Rekenwaarde van de belastingen
De rekenwaarde van de belasting moet zijn verkregen uit:
voor permanente belasting: $G_{d;u} = \gamma_{f;g;u} \times G_{rep;u}$ in de uiterste grenstoestand;
$G_{d;ser} = \gamma_{f;g;ser} \times G_{rep;ser}$ in de bruikbaarheidsgrenstoestand;
voor veranderlijke belasting: $Q_{d;u} = \gamma_{f;q;u} \times Q_{rep;u}$ in de uiterste grenstoestand;
$Q_{d;ser} = \gamma_{f;q;ser} \times Q_{rep;ser}$ in de bruikbaarheidsgrenstoestand;
voor bijzondere belasting: $A_{d;u} = \gamma_{f;a;u} \times A_{rep;u}$ in de uiterste grenstoestand;
$A_{d;ser} = \gamma_{f;a;ser} \times A_{rep;ser}$ in de bruikbaarheidsgrenstoestand.

Representatieve waarde van belastingen

Permanente belastingen

$$G_{rep;u} = A \cdot h \cdot \rho \cdot g$$

$G_{rep;u}$ representatieve waarde eigen gewicht
A oppervlakte van het constructie onderdeel
h de hoogte van het constructie onderdeel
ρ het soortelijk gewicht van het materiaal
g gravitatie kracht

Veranderlijke belastingen

$$P_{rep} = C_{\dim} \cdot C_{index} \cdot C_{eq} \cdot \Phi_i \cdot P_w$$

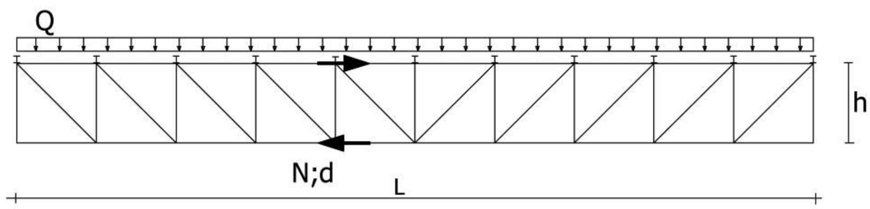
waarin:
p_{rep} is de windbelasting door winddruk, windzuiging, windwrijving en over- of onderdruk, in kN/m2;
C_{dim} is de factor die de afmetingen van een bouwwerk in rekening brengt, te bepalen volgens 8.6.3;
C_{index} zijn de windvormfactoren; deze kunnen zijn:
C_{pe} voor externe druk of zuiging op vlakken, te bepalen volgens 8.6.1.3.2;
$C_{pe;loc}$ voor lokale situaties in vlakken, te bepalen volgens 8.6.1.3.2;
C_{pi} voor interne over- of onderdruk, te bepalen volgens 8.6.4.4;
C_f voor wrijving, te bepalen volgens 8.6.4.5;
C_t voor een combinatie van voornoemde vormfactoren zodat de totale windbelasting als een geheel wordt beschouwd, te bepalen volgens 8.6.1.3.2;
C_{eq} is de drukvereffeningsfactor, te bepalen volgens 8.6.5.1;
φ_1 is de vergrotingsfactor die de dynamische invloed van wind in de windrichting op het bouwwerk in rekening brengt. Voor een bepaling van de waarde van φ_1 wordt verwezen naar 8.6.6;
p_w is de extreme waarde van de stuwdruk te bepalen volgens 8.6.2, in kN/m2;

	Veiligheidsklasse	Belastingcombinaties volgens 6.3.4	Yf;g;u(Yf;p;u)		Yf;q;u	Yf;a;u
			Normaal	gunstig		
Fundamentele belasting combinatie	1	1	1,2	0,9	1,2	-
	2	1	1,2	0,9	1,3	-
	3	1	1,2	0,9	1,5	-
	1 , 2, 3	2	1,35	0,9	`-	-
Bijzondere belasting combinatie	1 , 2, 3	3	1.0	1.0	1.0	1.0

	Veiligheidsklasse	Belastingcombinaties volgens 6.3.5	Yf;g;ser		Yf;q;ser	Yf;a;ser
			Normaal	gunstig		
Incidentele combinatie	1 , 2, 3	4	1.0	1.0	`1.0	-
Momentane **combinatie**	1 , 2, 3	5	1.0	1.0	1.0	-

Calculation truss Jellema deel 9 p 169

Figure 1 Truss calculation



$$N_d = \frac{Q_{d;u} l^2}{8h}$$

Calculation deflection ASTM E1300-94

$$\omega_{\max} = \frac{1}{175} L$$

l overspanningslengte

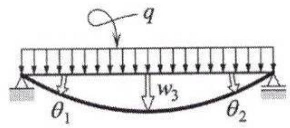
$$\omega_{opt} = \frac{5}{384} \frac{Q_{d;u} l^4}{EI}$$

$Q_{d;u}$ rekenwaarde windbelasting
l lengte waarover de windbelasting verdeeld is
E Elasticitetismodulus
I Traagheidsmoment

Controle

$$\omega_{\max} > \omega_{opt}$$

Figure 2
Deflection



Calculation buckling NEN6770

$$F_e = \frac{\pi^2 E_{glass} I_{glass}}{l_c^2}$$

$$\lambda = \sqrt{\frac{N_d}{F_e}} \Rightarrow \omega_{buc}$$ NEN6770 figuur 42

$$\frac{N_d}{\omega_{buc} \cdot A_{glass} \cdot f_{d;glass}} \leq 1$$

Appendix E Calculation table

Input compression tube perpendicular to façade, small arm

Design strength glass(fd)	20	N/mm²		
F;rep				
Wind pressure	0,62	kN/m²	1,674	kN
Wind suction	-0,4	kN/m²	-1,08	kN
Dimensions				
Length	10	m		
Width	12,8	m		
Centre to centre width	1,8	m		
Centre to centre heigth	1,5	m		
h press	0,39	m		
h suction	-0,39	m		
E	64000	Mpa		
I	48576,39	mm4		
omega ω	0,9			
G	0,005993	kN/m¹		
σc=ωfd	18	N/mm²		
σc=Nd/A				
Density	22	kN/m3		
Lk width small	780	mm		
Lk width large	1800	mm		

Determintation I

tube	
r binnen	17,7
r buiten	20
A	272,4075
I eigen	48576,39
I totaal	48576,39

cable	
r	0
A	0
I eigen	0
I steiner	0
I tot kabel	0

			Pressure				Suction	
Ultimate state limit:			kN	kN			kN	kN
Dead load	1,35G		0,080905				0,080905	
Dead load + wind	1,2G+1,5F;rep		0,071916	2,511			0,071916	-1,62
Serviceability state limit:								
Dead load + wind	1,0G+1,0F;rep		0,05993	1,674			0,05993	-1,08
σ=N;d/A	A=			**139,5**	mm2	<340mm2		90mm2

Controle knik width Short x								
Fe	(π²EIglass)/lk²			50,43311	kN			
λ	√Nd/Fe			0,223134		NEN6770		
ωbuc=1 volgens kromme fig42	Nd/ωbuc*(A*fdglass)			**0,5121**		<1	Voldoet!	

Input main tube

Design strength glass(fd)	20	N/mm²			
Design strength Cable(fd)	1770	N/mm²	NEN3575		
F;rep					
Wind pressure	0,62	kN/m²		1,116	kN/m
Wind suction	-0,4	kN/m²		-0,72	kN/m
Dimensions					
Length	10	m			
Width	12,8	m			
Centre to centre	1,8	m			
h press	0,39	m			
h suction	-0,39	m			
E	64000	Mpa			
I	55849073,57	mm4	hoofdstaaf met zijstaven staal		
omega ω	0,9		150x5tube		
G	0,069184153	kN/m¹	150x5tube		
σc=ωfd	18	N/mm²			
σc=Nd/A					
Density	22	kN/m3			
Lk	1800	mm			

Determination I

buis	
r binnen	68
r buiten	75
A	3144,7342
I eigen	8057595,3
I totaal	55849074

kabel	
r	10
A	314,1593
I eigen	7853,982
Isteiner	47783624
I tot kabel	47791478

Ultimate state limit:		kN	kN/m¹		kN	kN/m¹	
Dead load	1,35G	0,933986			0,9339861		
Dead load + wind	1,2G+1,5F;rep	0,83021	1,674		0,8302098	-1,08	
Serviceability state limit:							
Dead load + wind	1,0G+1,0F;rep	0,691842	1,116		0,6918415	-0,72	
Ultimate state limit:			Nd	A		Nd	A
N;d	(ql2)/(8h)+deadload		0,933986071	51,88812	mm²	0,933986	51,88812
N;d	(ql2)/(8h)+deadload		54,48405599	3026,892	mm²	35,44559	1969,2
Serviceability state limit:							
Deflection<58mm			40,65435051	mm			

Oppervlakte kabel			
Ultimate state limit:			
N;d/f;d		0,527675746	mm²
N;d/f;d		30,78195254	mm²

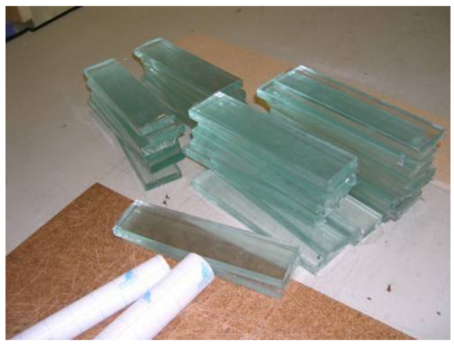
Controle knik						
Fe	(π²EIglass)/lk²		1570,869694	kN		
λ	√Nd/Fe		0,186236429		NEN6770	
ωbuc=1 volgens kromme fig42	Nd/ωbuc*(A*fdglass)		0,962527121		<1	Voldoet!

Appendix F Preliminary experiments

1.1 Introduction

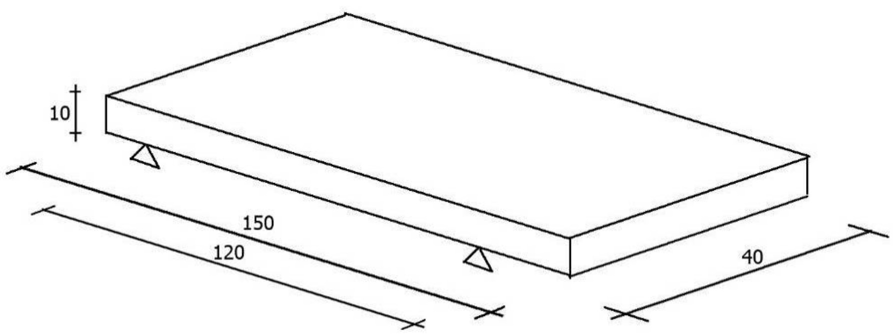
In this research part 40 glass specimen of annealed float glass are tested. The specimens were cut manually using an oil lubricated glass cutter. The edges in longitudinal direction were already grinded; the edges in wide wise direction were not grinded. The last one would not have influence in the strength because of the way of testing. All specimens were wrapped up in plastic to avoid glass splinters to fly.

Figure 1 Wrapped specimens



The specimen size and the support separation are illustrated in 0. With the help of 4-pointbending and 3-pointbending tests the strength of the glass is measured. In each test 20 specimens are tested. All specimens were tested in a ZWICK Z010 and Testexpert software.

Figure 2 Specimen sizes



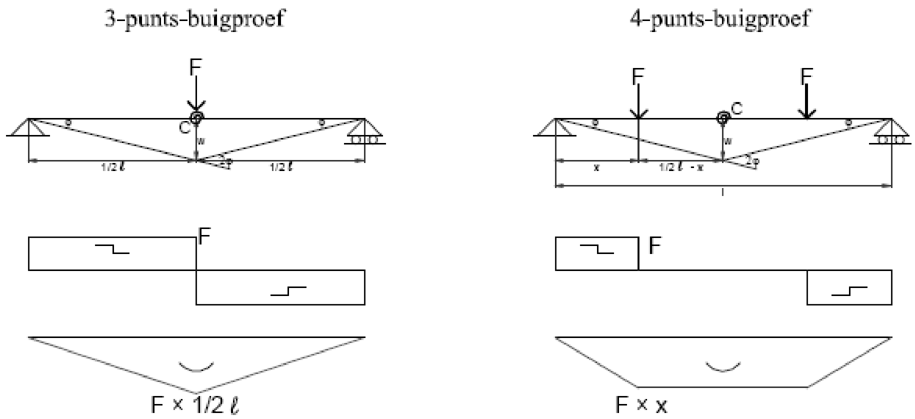
l

= 150 mm, l_{opl} = 120 mm, b= 40 mm, h = 10 mm

The difference between a 3-point an 4point bending test are graphically shown in 0

Figure 3
3-point bending test

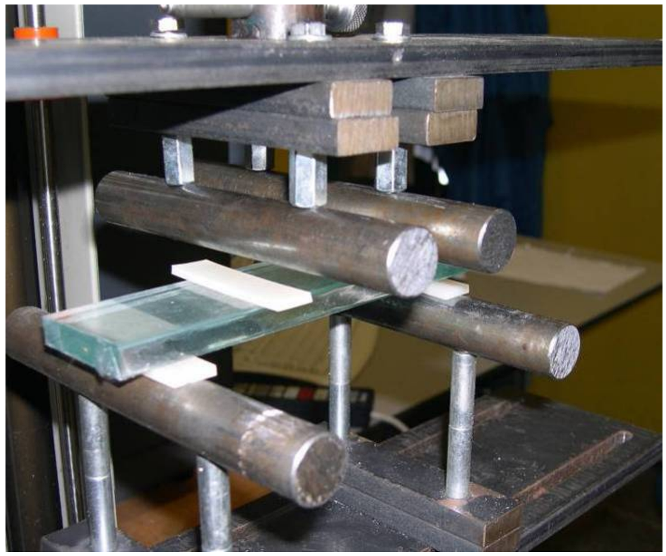
Figure 4
4-point bending test



1.2 4-point bending test

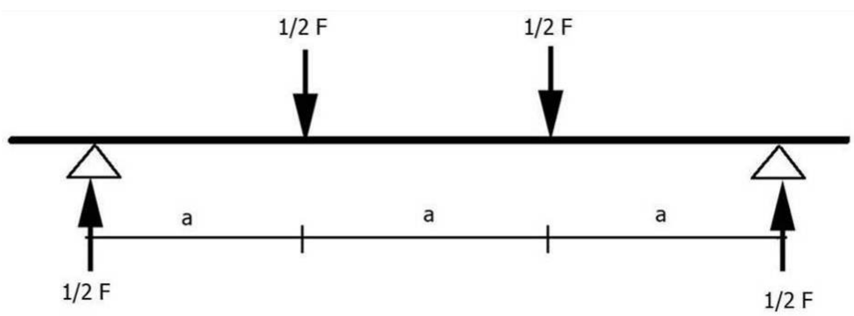
The support separation was manually set on 120mm and the force source separation at 40 mm, 1/3 of the span. Before starting testing, data of the specimen and the test are inserted in the test program Testexpert. On the supports and the force sources silicon rubber is placed to avoid direct contact with the steel.

Figure 5 Test rig for 4-Point bending test



Expectation failure force

Figure 6 Scheme testset-up



$W = 1/6\ b\ h^2$ *(1)*
$M = ½\ F\ a$ *(2)*
$\sigma = M / W$ *(3)*

Assumption stress: $\sigma \approx 45\ N/mm^2$
$a = 1/3\ l_{opl}$
$a = 40$
$W = 1/6 \times 40 \times 10^2 = 666{,}667 mm^3$
$M = ½\ F \times 40 = 20\ F$
$20F = 45 \times 666{,}667$
F = 1499N ≈ 1.5kN

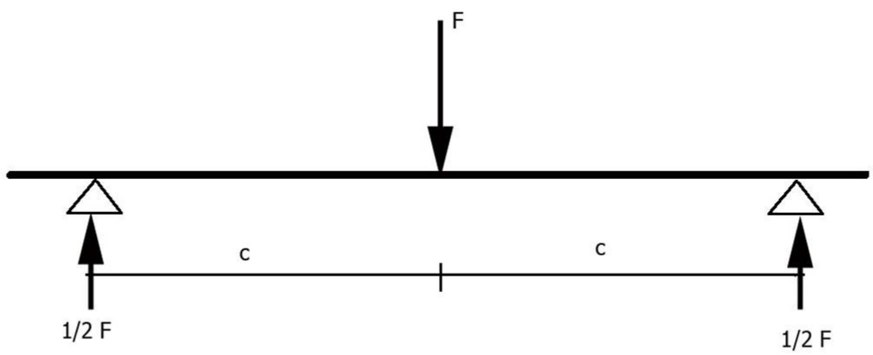
1.3 3-point bending test

The support separation stayed on 120mm and the force source was set at 1/2 of the span. The data of the test are changed into a 3-pointbending test. On the supports and the force source silicon rubber is placed to avoid direct contact with the steel.

Figure 7 Test rig for 3 point bending test

Expectation failure force

Figure 8 Scheme testset -up



$$W = 1/6\ b\ h^2$$
$$M = ½\ F\ c$$
$$\sigma = M / W$$

Assumption stress: $\sigma \approx 45$ N/mm^2
$c = 1/2\ l_{opl} = 60$
W= 1/6 x 40 x10^2 = 666,667mm^3
M = ½ F x 60 = 30 F
30 F = 45 x 666,667
F = 999N ≈ 1.0 kN

1.4 Test results February 8th

4-point bending test

Nr Specimen	b	h	F (N)	M (Nmm)	I (mm4)	σ (N/mm2)	Displacement rate (mm/min)
1	40,42	10,3	1520	30400	3680,669	42,53575	0,5
2	40,48	10,16	2480	49600	3537,858	71,2205	1
3	41,17	10,04	3240	64800	3472,168	93,6867	2
4	40,73	10,16	3180	63600	3559,707	90,76252	2
5	40,99	10,18	3220	64400	3603,628	90,96276	2
6	41,02	10,57	1830	36600	4036,82	47,91668	2
7	40,7	10,07	1630	32600	3463,391	47,39314	2
8	40,7	10,08	2820	56400	3473,72	81,83044	2
9	40,78	10,04	4310	86200	3439,277	125,8183	2
10	40,8	10,11	1990	39800	3513,439	57,2627	2
11	40,96	10,12	3690	73800	3537,694	105,5569	2
12	41,13	10,1	2120	42400	3531,357	60,63392	2
13	40,78	10,06	3230	64600	3459,871	93,91622	2
14	40,47	10,26	3410	68200	3642,454	96,05228	2
15	40,49	10,2	2590	51800	3580,693	73,77902	2
16	41	10,04	2990	59800	3457,831	86,81628	2
17	40,7	10,05	2330	46600	3442,796	68,01593	2
18	40,67	10,14	2730	54600	3533,514	78,34185	2
19	40,87	10,1	2590	51800	3509,033	74,54759	2
20	40,74	10,18	2520	50400	3581,65	71,62509	2

SOM			54420			1558,675	
Average Strength (MPa)			2721			77,93373	
SD (MPa)			693,4256			20,4227	

Table 1 Results 4pointbending test

Crack patterns 4-point bending test

Figure 9
Specimen 1-3

Figure 10
Specimen 4-6

Figure 11
Specimen 7-9

Figure 12
Specimen 10-12

Figure 13
Specimen 13-15

Figure 14
Specimen 16-18

Figure 15
Specimen 19-20

3-point bending test

Nr Specimen	b	h	F (N)	M (Nmm)	I (mm4)	σ (N/mm2)	Displacement rate (mm/min
21	40,94	10,06	2380	71400	3473,446	103,3965	2
22	41,3	10,06	1340	40200	3503,989	57,70737	2
23	40,54	10,1	1640	49200	3480,7	71,38219	2
24	40,8	10,14	2150	64500	3544,809	92,25181	2
25	40,35	10,06	2490	74700	3423,389	109,757	2
26	41,28	10,16	2190	65700	3607,776	92,51018	2
27	40,42	10,1	1620	48600	3470,397	70,72101	2
28	41,09	10,05	2620	78600	3475,786	113,6333	2
29	40,84	10,29	2020	60600	3708,093	84,08284	2
30	40,74	10,22	2120	63600	3624,036	89,67792	2
31	41,04	10,05	1940	58200	3471,557	84,24318	2
32	40,75	10,11	2620	78600	3509,133	113,2254	2
33	40,77	10,12	2030	60900	3521,284	87,51184	2
34	41,27	10,09	1750	52500	3532,862	74,97108	2
35	40,95	10,04	2900	87000	3453,614	126,4588	2
36	40,76	10,09	2320	69600	3489,205	100,6338	2
37	40,97	10,12	2260	67800	3538,557	96,95137	2
38	40,71	10,45	2620	78600	3871,406	106,0816	2
39	41,08	10,2	1420	42600	3632,869	59,80398	2
40	40,91	10,19	1810	54300	3607,205	76,69609	2

SOM			40900			1753,99	
Average Strength (MPa)			2152,632			92,31526	
SD (MPa)			388,1107			16,91147	

Table 2 test results 3pointbending test

Test 22 did not fail. The silicon rubber slipped away and the test rig stopped the measurement.

Crack patterns 3-point bending test

Figure 16
Specimen 21-22

Figure 17
Specimen 24-26

Figure 18
Specimen 27-29

Figure 19
Specimen 30-32

Figure 20
Specimen 33 -35

Figure 21
Specimen 36-38

Figure 22
Specimen 39-40

1.5 Conclusion

Conclusion 4-point bending test

The edges of flat glass are the weakest, because of the cutting process. The flat surfaces are much stronger because of smaller defects. Glass, after cutting, is never perfectly straight and after grinding these differences in the edges will not completely be rubbed out. That is why normally the cracks start from an edge point in the tensile zone and are fan shaped. Between the force sources the maximum moment is located and failure occurs in that area. The fan shaped area of the highest failure strength shows many more cracks and the crack area is bigger.

Figure 23
Crack highest failure strength

Figure 24
Crack lowest failure strength

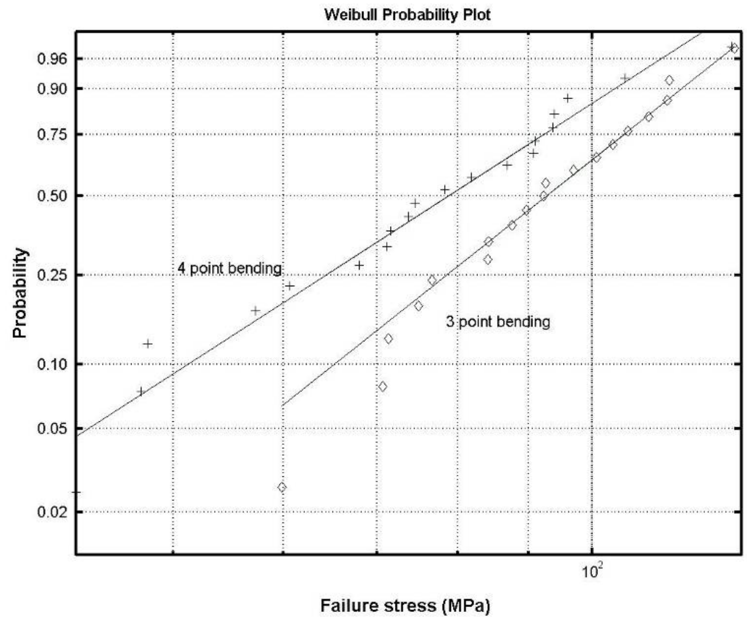
Conclusion 3-point bending test

The maximum moment occurs in the centre of the specimen, but not all specimen fail in the centre. Specimens that failed within a distance of the centre have a clear defect in that point. This means that the actual stress at that point is are much lower. Also in this test the cracks are fan shaped. And the crack area of the highest failure strength is also bigger.

Figure 25
Crack highest failure strength

Figure 26
Crack lowest failure strength

Graph 1
Weibull probability plot.



According to Veer *(strength and failure of glass in bending)* specimen that fail at lower strength have some rare type of defect. An explanation for this is that there are several kinds of failure mechanisms and possibly associated with different types of defect causing the initial failure. It is hard to study the glass edges and surfaces, because of its transparency and the very small cracks.

A 3-point bending stress will give a higher design strength, but there is also a clear deviation at the lower bound. The maximum stress in a 3 point bending stress is concentrated in the centre, but this does not mean it will break in the centre. A 4-point bending test gives a lower design strength, but also follows the Weibull line quite well.

Table 1
Design strength

	Mean failure stress (MPa)	Standard deviation (MPa)	Weibull strength (MPa)
4point bending	78	20	20
	92	17	25

Appendix G FEM output

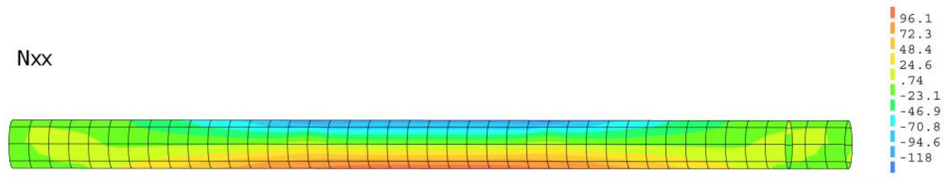


Figure 1
Nxx

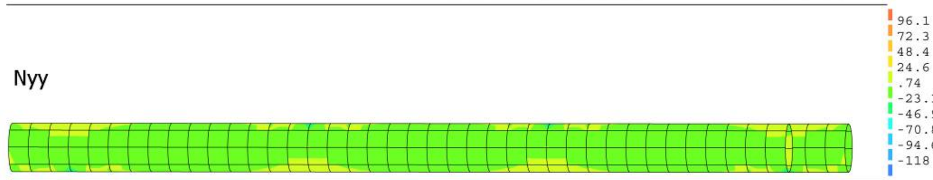


Figure 2
Nyy

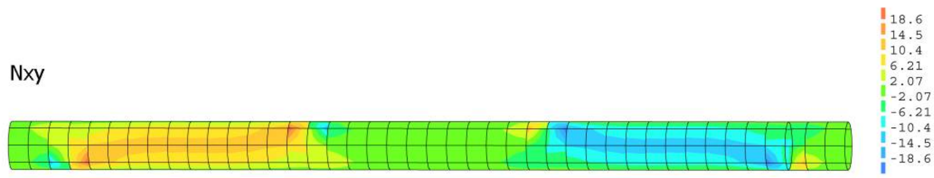


Figure 3
Nxy

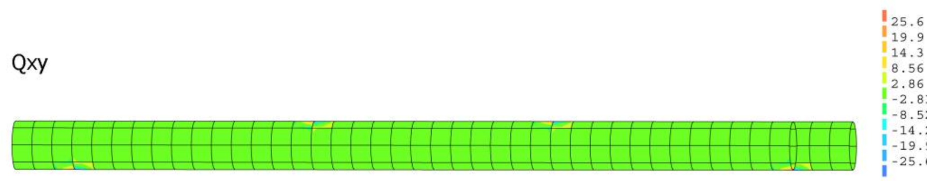


Figure 4
Qxy

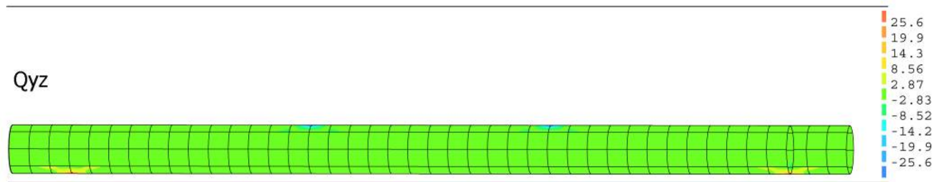


Figure 5
Qyz

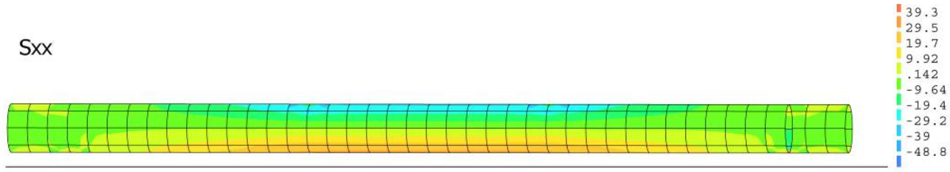


Figure 6
Sxx

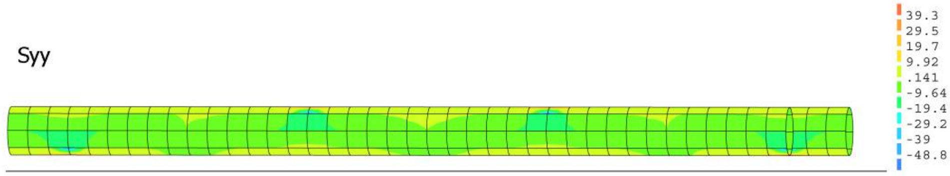


Figure 7
syy

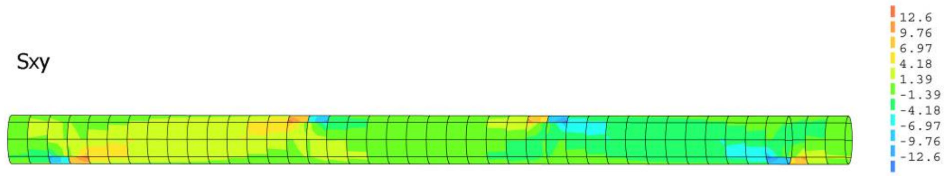


Figure 8
sxy

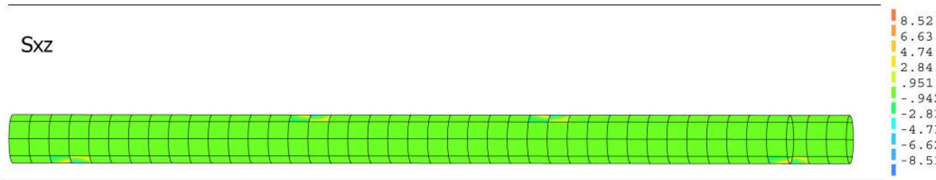


Figure 9
sxz

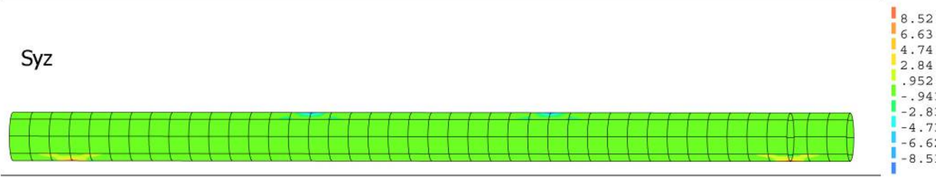


Figure 10
syz

Figure 11
Nxx

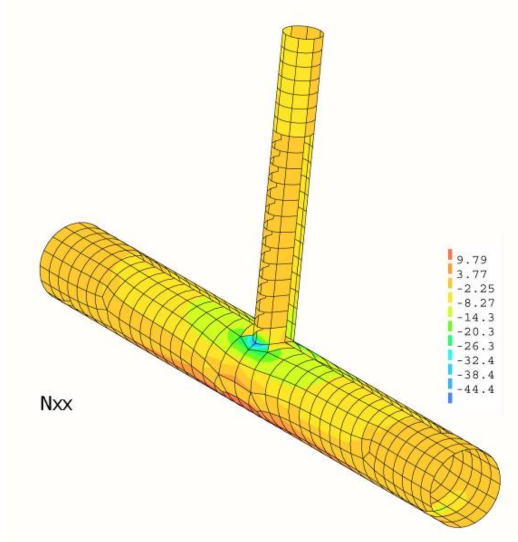


Figure 12
Nyy

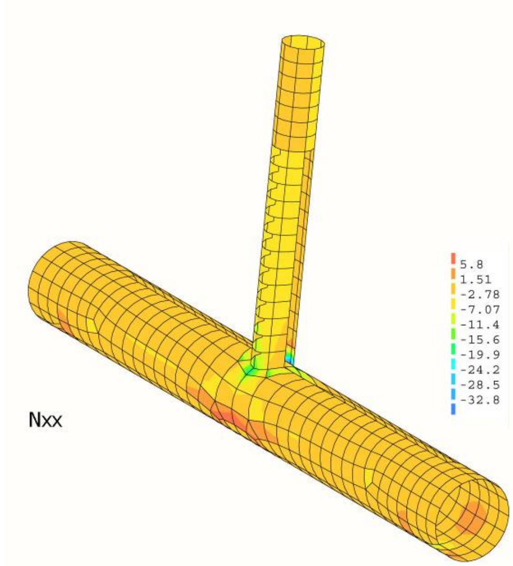


Figure 13
Nxy

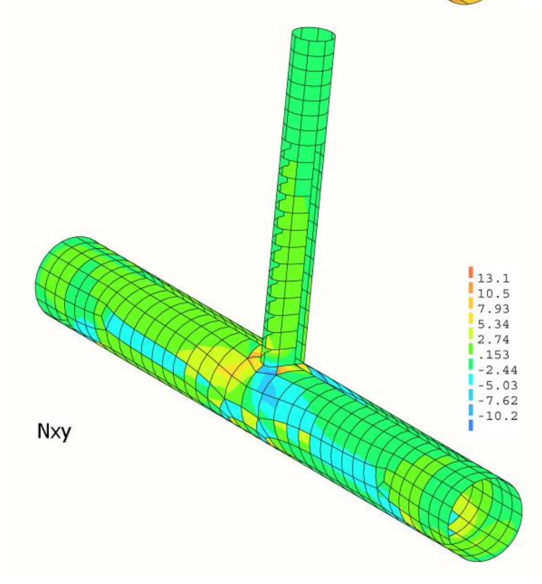


Figure 14
Qxz

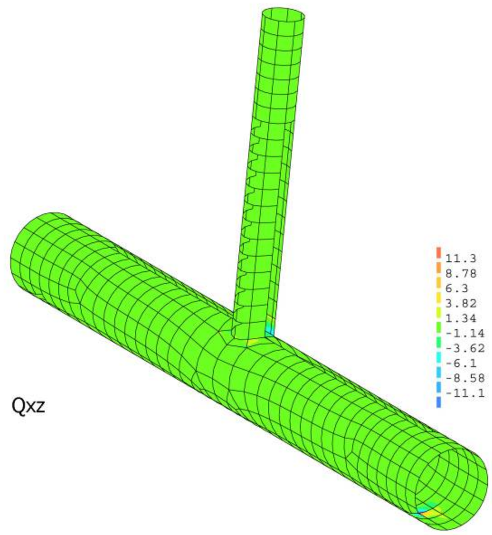


Figure 15
Qyz

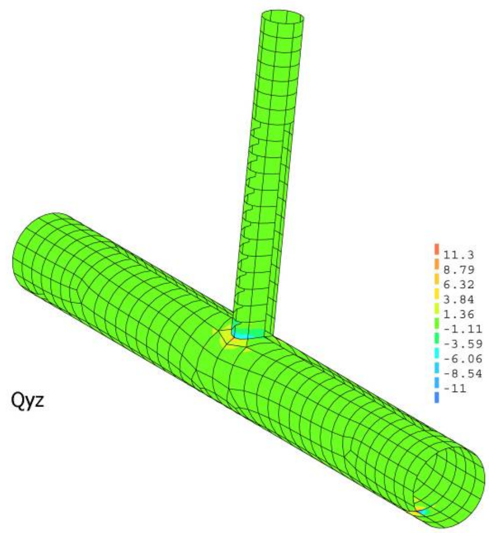


Figure 16
sxx

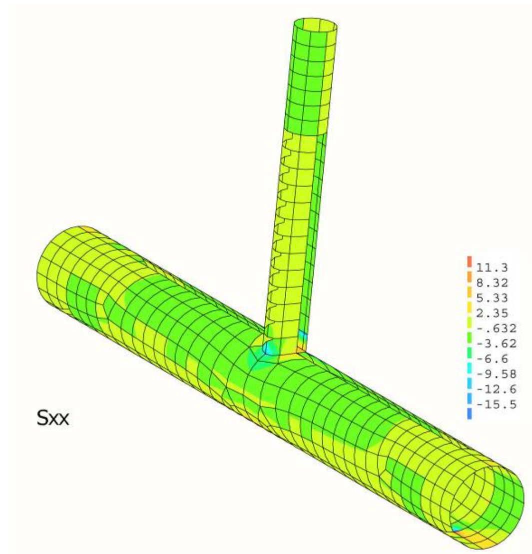


Figure 17
syy

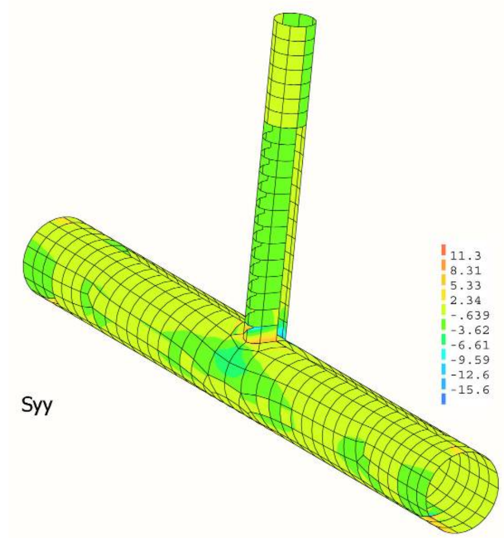


Figure 18
sxy

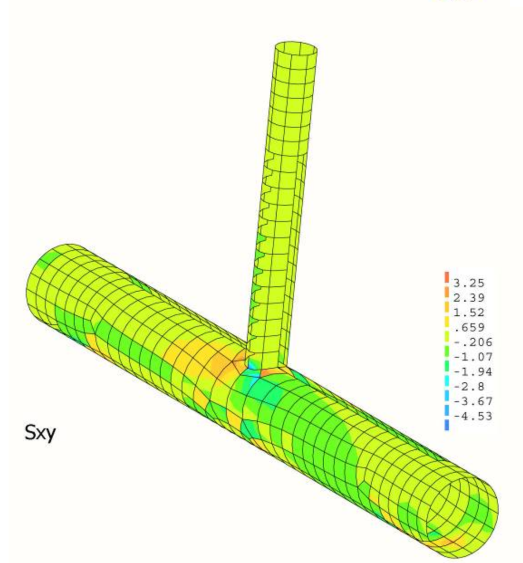


Figure 19
szx

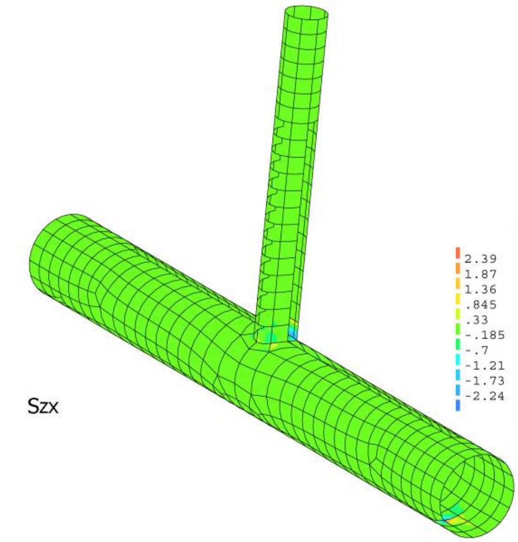


Figure 20
syz

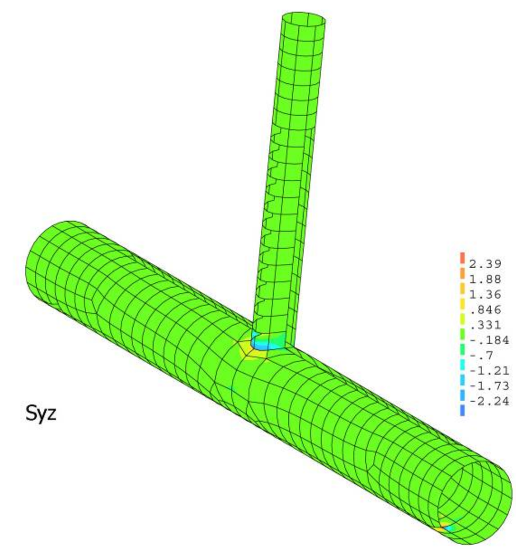
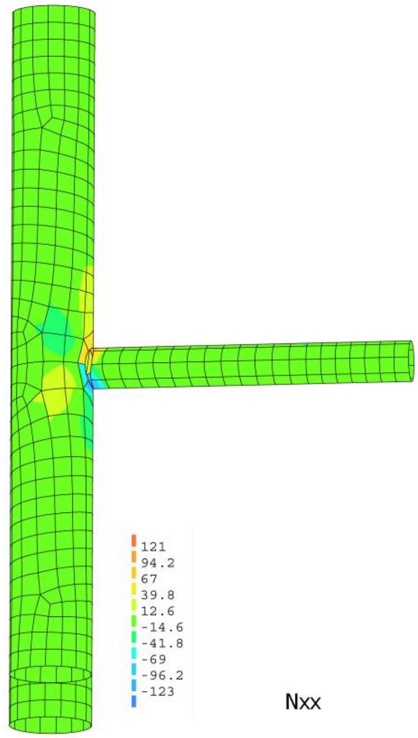


Figure 21
Nxx

Figure 22
Nyy



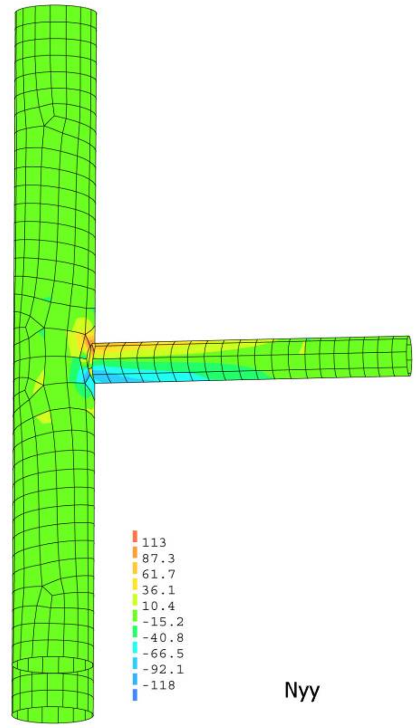


Figure 23
Nxy

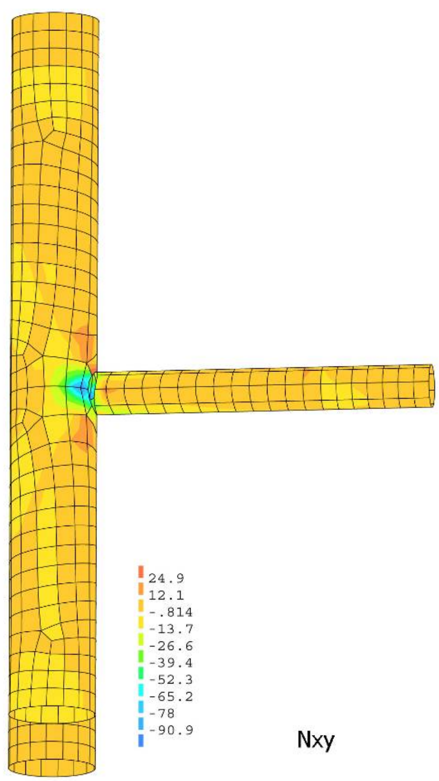
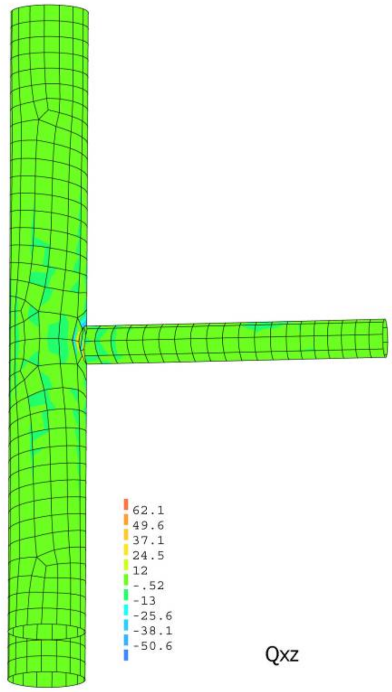


Figure 25
Qxz

Figure 26
Qyz



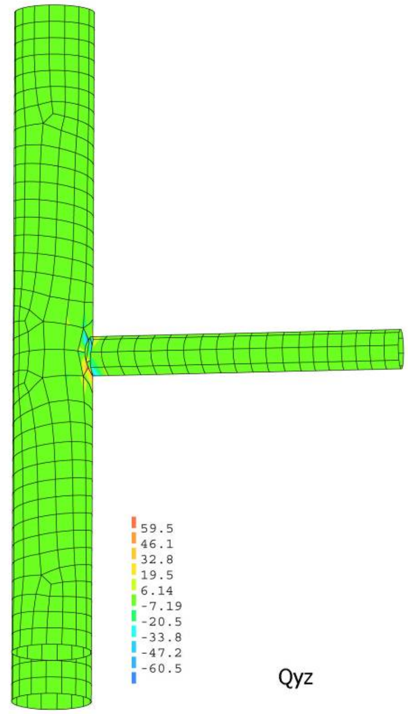
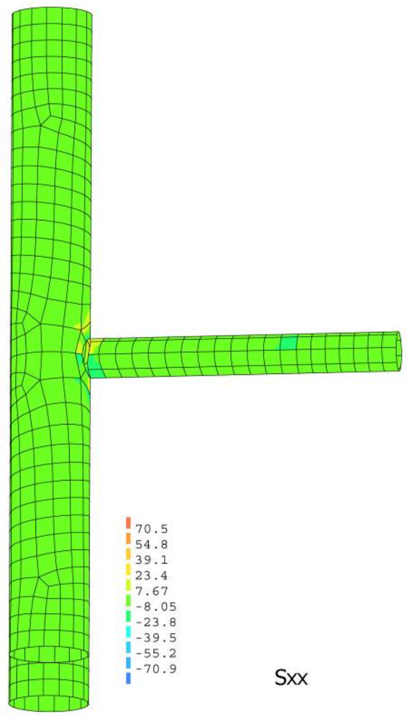


Figure 27
Szz

Figure 28
syy



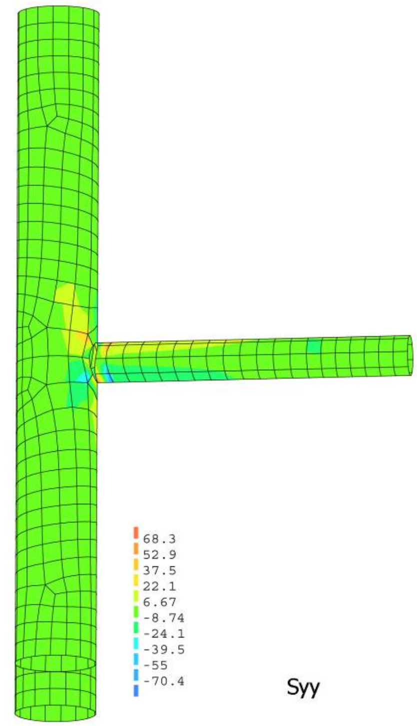
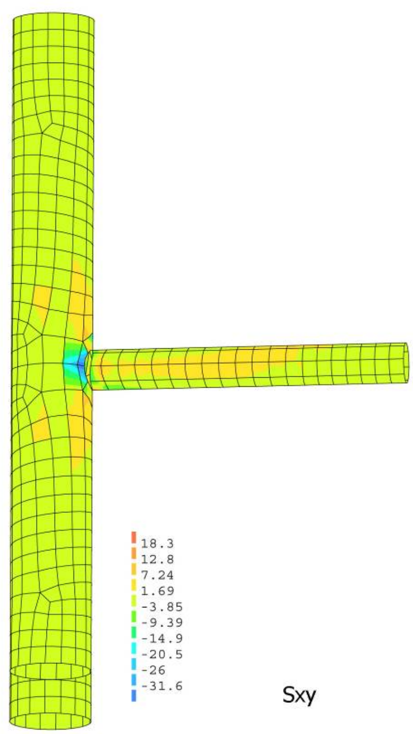
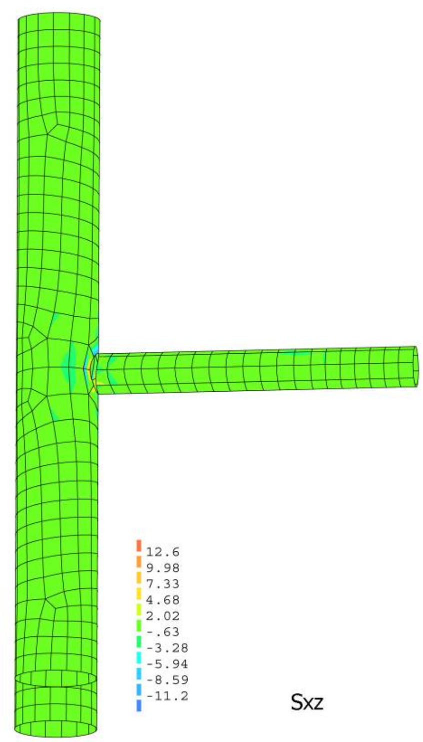


Figure 29
sxy

Figure 30
sxz





Appendix H Strain gauges

Mounting the strain gauges

Figure 1
Cleaning

Figure 2
Gluing

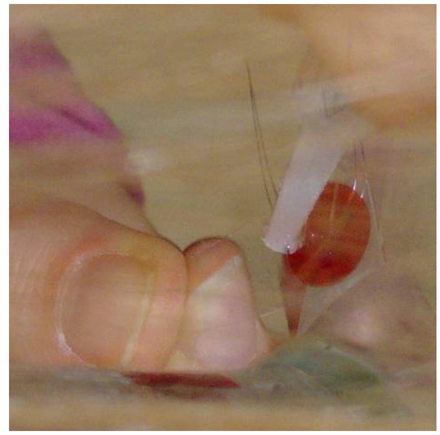


Figure 3
Holding

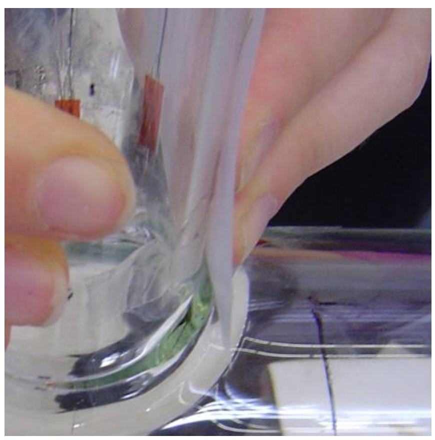


Figure 4
Removing the tape

Figure 5
Checking if mounted

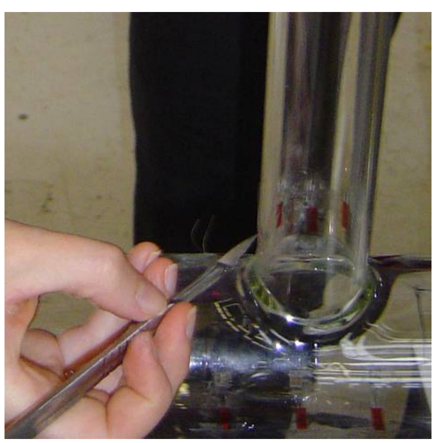


Figure 6
Soldering

Results strain gauges

4 point bending test

Ce04	1	2	3	4
Strain($x10^{-6}$)	8,44512	-58,3481	-182,125	719,2
E(N/mm^2)	64000	64000	64000	64000
σ (N/mm^2)	0,540488	-3,73428	-11,656	46,0288

Ce05	1	2	3	4
Strain($x10^{-6}$)	-4,60643	-12,2838	-86,8	356,5
E(N/mm^2)	64000	64000	64000	64000
σ (N/mm^2)	-0,29481	-0,78616	-5,5552	22,816

Compression test

Ce06	Strain(10^{-6})	E(N/mm^2)	σ (N/mm^2)
1	-596,75	64000	-38,19
2	-217,775	64000	-13,94
3	70,525	64000	4,51
4	-465	64000	-29,76
5	-319,3	64000	-20,44
6	-453,375	64000	-29,02
7	-221,65	64000	-14,19
8	-224,75	64000	-14,38
9	420,825	64000	26,93

Ce07	Strain(10^{-6})	E(N/mm^2)	σ (N/mm^2)
1	-458,025	64000	-29,31
2	-347,2	64000	-22,22
3	11,625	64000	0,74
4	-697,5	64000	-44,64
5	-466,55	64000	-29,86
6	-578,925	64000	-37,05
7	-200,725	64000	-12,85
8	-334,8	64000	-21,43
9	571,95	64000	36,60

Moment test

Ce02	Strain($x10^{-6}$)	σ (N/mm^2)
1	176,58	11,30
2	223,412	14,30
3	144,925	9,28
4	21,7	1,39
5	-141,825	-9,08
6	-236,463	-15,13
7	-347,017	-22,21
8	520,8	33,33
9	596,75	38,19
10	53,475	3,42
11	-616,9	-39,48
12	-905,975	-57,98
13	-55,8	-3,57
14	-6,975	-0,45
15	-31,775	-2,03

Ce03	Strain($x10^{-6}$)	σ (N/mm^2)
1	386,172	24,72
2	221,108	14,15
3	224,75	14,38
4	30,225	1,93
5	-127,875	-8,18
6	-317,076	-20,29
7	-427,63	-27,37
8	940,85	60,21
9	655,65	41,96
10	-96,1	-6,15
11	-705,25	-45,14
12	-887,375	-56,79
13	21,7	1,39
14	-7,75	-0,50
15	-43,4	-2,78

Appendix I Statistics

The prediction of product life can be expressed with the help of statistics. Products in large manufacture quantities have a variable life and the failure of components is also subjected to variations.

There are several kinds of statistical distributions, like the exponential, normal, Poisson's and Weibull distributions.

After testing a statistical approach on the test results will be given. This will lead to a certain distribution and with that any certainty can be given with regard to the strength.

To show the amount of variety in the test results, the standard deviation is used:

$$S_n = \sqrt{\frac{1}{1-n} \cdot \sum_{i=1}^{n} (X_i - \overline{X})^2}$$

A statistical distribution can be used to describe the behaviour of a particular event or property. This behaviour is translated into a probability distribution, due to the several unknown parameters.

To describe the strength of a material

The strength of glass is often described by the Weibull distribution. In this distribution it is possible to show more processes. Because the strength of glass is depended on the surface condition and its geometry it can be expressed in a Weibull distribution instead of a normal or exponential distribution. The normal distribution predicts a small probability of failure even at zero stress and therefore the probabilities of breakage were notional and did not represent the actual failure probability at a selected strength *(fallacy of the weibull distribution for window glass design).* According to earlier research *(quality control and the strength of glass)* by Veer, describing the strength of glass by Weibull can not be done in every case because you can not read out the way of failure, by defects in joint, surface condition, thickness of joint.

The probability density function is:

$$f(x;k,\lambda) = (k/\lambda)(x/\lambda)^{(k-1)}e^{-(x/\lambda)^k}$$

The distribution function is:

$$F(x;k,\lambda) = 1 - e^{-(x/\lambda)^k}$$

Where $x \geq 0$ and $k > 0$ the shape parameter is and $\lambda > 0$ the scale parameter is of this distribution.