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# **Parametric Study of Bolted and Adhesive Connections and Experimental Creep Tests in Adhesive Connections under High Temperature and Long Term Loading**

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia Civil na Especialidade de Mecânica Estrutural

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## **SIMBOLOGIA**

$\varepsilon$  – Deformation

$\sigma_{Ra}$ - Failure stress

$\sigma_{Res}$ - Residual stress

$\sigma_{ED}$  – Imposed stress

$\rho$  – Density

H – Distance from center of the hole until edge of the glass

D – Diameter of the hole or connection

h – Height of the glass panel

E – Young Modulus

t – Thickness of the glass panel

ta – Thickness of the adhesive

## **ABREVIATURAS**

SGE – Embedded SentryGlas specimen

SGC - Centered SentryGlas specimen

TSSAC – Centered TSSA Specimen

MGS – Maximum glass stress

MAS – Maximum Adhesive stress

GP – Glass Panel

GC – Glass Connection

## **Abstract**

Recently glass has been the object of a lot of interest for its transparent capability and as such a lot of research is being done in order to facilitate its utilization in facades, beams, stairs and other structural elements. Connections are a key point of this research since they condition the overall structure's dimensions, leading engineers to often oversizing the structure.

The adhesive connections in particular are being very investigated due to its advantages in terms of architecture and stress distribution. However there are still a lot of factors that without further investigation prevent its use without other safety mechanisms in structures. One of these factors is the behavior of the adhesives under high temperatures.

Because of these needs in glass investigation, the thesis will be divided into two different areas:

-For facades, both adhesive and bolted connections parametric studies will be conducted in order to assess the optimized dimension of the different parameters. This study will lead to an easier assessment in project of the typologies to choose as well as its geometry for early design.

The parametric study will be made with the help of FEM models for both connection types, leading to a faster iteration in glass design.

-For adhesive connections, experimental studies under high temperatures with glass samples with different geometries and different adhesives will be conducted in order to predict failure.

## Resumo

Recentemente o vidro tem sido alvo de um grande interesse pela sua capacidade de transparência e, como tal, uma série de pesquisas está a ser desenvolvida de forma a facilitar sua utilização em fachadas, vigas, escadas e outros elementos estruturais. As ligações são um ponto-chave desta investigação, uma vez que condicionam as dimensões da estrutura geral, muitas vezes sobre dimensionando a estrutura.

As ligações adesivas em particular estão a ser muito investigadas devido às suas vantagens em termos de arquitetura e distribuição de tensões. No entanto ainda existem muitos fatores que, sem investigação mais extensiva impedem a sua utilização sem outros mecanismos de segurança em estruturas. Um destes fatores é o comportamento de ligações adesivas sob altas temperaturas.

Devido a estas necessidades na investigação do vidro, a tese será dividida em duas áreas diferentes.

-Para fachadas tanto para ligações adesivas como aparafusadas, serão realizados estudos paramétricos com o fim de avaliar a dimensão otimizada dos diferentes parâmetros. Este estudo vai levar a uma avaliação mais fácil numa fase inicial de projeto das tipologias a escolher, bem como para a sua geometria.

O estudo paramétrico será feito utilizando modelos FEM para ambos os tipos de ligações. Levando a uma iteração mais rápida em dimensionamento de estruturas em vidro.

-Para ligações adesivas, estudos experimentais sob altas temperaturas com amostras de vidro de geometrias e tipos de adesivos diferentes serão conduzidos de modo a prever cedência.



## 1. Introduction

### 1.1. General work significance

In the last decade, structural glass has gained more importance due to its increasing need in architecture for its transparency and aesthetics. Structural glass provided the solution for this need, as technology advanced, becoming a much more reliable and stronger material, present in most important recent buildings. With this increasing need of transparency, the architecture of buildings evolved to have the least opaque elements in facades possible, with less visual impact of the supporting substructure. This eventually led to a full glass facade solution with the substructure also in glass, leading into different engineering challenges in safety, transparency and economy.

It's important to predict accurately the behavior of the structure not only in terms of local or global failure (ULS) but also in terms of serviceability (SLS).

Reducing the quantity of opaque elements in order to increase the structure's transparency reflects the need to decrease the thickness of the glass and design of connections.

As for economy, it presents one of the biggest challenges seeing that the prevision models used nowadays are still unreliable leading to big security factors that reflect in an oversizing of glass thickness and connections' dimensions.

Theoretically, glass would have a tensile strength of 32 GPa, but, since it is a brittle material, its resistance will be very limited by the mechanical flaws existent. The macroscopic flaws imposed, including the holes used for bolted connections, lead to a diminution of glass' admissible stress around the hole and an increase in stress concentration due to imperfections. These factors make the location of the connection a critical place for glass failure.

Adhesive connections overcame some of these drawbacks and, furthermore allow for a smooth surface without any visible connections in the outer part of a facade.

In spite of this, the use of adhesive joints is not as broad as one would expect, mainly due to the lack of knowledge of its behavior in some environments. Since it's a relatively new connection type its behavior hasn't been properly studied in some actions to which the structure could be subjected to. These actions include high temperature, UV radiation, moisture, long term loading and others. For these reasons, the research on the behavior of adhesive joints has increased in the last few years.

The work presented in this thesis is within this framework, and aims to better understand adhesive connection for glass application subjected to high temperatures and long term behavior in adhesives.

## **1.2. Work and objectives**

As referred in the abstract, due to this increasing need in glass investigation, the thesis will be divided into two different parts:

- Given the importance geometrical parameters have in a connection and, therefore, in the design of the structure as a whole, this study will be focused in a parametrical analysis of two main types of connections: bolted and adhesive. The conclusions will assist the engineer the early stage and help guiding the decisions concerning the choice of typology and geometry of the joint.

For the envisaged study, it is considered that the joints are joints in facades. The selection of this structural element as base connecting element has to do with the fact it is very common.

Regarding the connections, bolted connections were chosen due to the fact they are the most frequently used and adhesive because it is a very good alternative with increasing demand in comparison with other connectors.

The parametric study will be made with the help of FEM models for both connection types, leading to a faster iteration to an optimized solution in glass design.

Given the influence adhesives suffer from long term and temperature effects, the present thesis will also include the investigation of these aspects. Thus for adhesive connections, experimental studies under high temperatures with glass samples with different geometries and different adhesives will be conducted in order to characterize and predict failure. The results will allow for a better uptake on the viscoelastic properties of the studied adhesives under high temperature and long term load application.

The general work will be structured as following:

- Chapter 1 contains the introduction.
- Chapter 2 contains the state of the art of each of glass and connection typologies.
- Chapter 3 contains the material's properties used in the models.
- Chapter 4 will focus on the facade study, describing elements and geometries.
- Chapter 5 features the assumptions used in the creation of the FEA models with the program Abaqus.
- Chapter 6 includes the results for both the parametric studies and discussion of results.
- Chapter 7 contains the conclusions of the parametrical analysis.
- Chapter 8 defines the subjects for the creep test.and its conclusions.

## 2. State of the art

### 2.1. Glass

Glass is an amorphous, homogeneous and isotropic material product of fusion, cooled to a rigid condition without crystallization. Most of the glass used is soda lime silica glass which is used normally structurally and is studied in this thesis. The most important factor about this glass is that it has a linear elastic material behavior with brittle fracture. More information about glass' properties can be found in [1];[2].

Even although glass has theoretically a tensile strength of 32 GPa, the inherent flaws caused by the fabrication procedure of the material, cause a great diminution of the resistant stress. Since these inherent flaws can't be accurately predicted, probabilistic methodologies are used to predict the stress limit in glass. Aside from the flaws invisible to the naked eye, other factors change the resistance of glass, among such: Temperature, stress corrosion, humidity, imposed macroscopic flaws, edges of glass.

In perfect conditions, without any air humidity, the strength in glass behaves independently from time. However, considering humidity, the cracks in glass are allowed to grow when exposed to an opening crack stress. This means that even with a stress bellow critical, the glass will still fail after the necessary time for the crack to become critical. The allowed stress in glass diminished over time at a speed already defined. This chemical process is called stress corrosion.[3]

Stress corrosion is a factor to always have in consideration since glass is very affected by it. Depending on the duration of the load application, glass resists less throughout time. The relative average strength is considered for a load duration of 10 minutes.[4]

Annealed glass is the basic float glass, being slowly cooled during fabrication process in order to relieve any internal stresses. This type of glass has a nominal resistance of 45MPa until it is further processed, namely through heat treatment or, more often called, tempering.

In structural glass, tempering is the most important processing method. By heating and slowly cooling the glass, a residual stress field is imposed on the glass as seen in the picture bellow with tension in the core and compression in the surface. The stress field created is non-linear across the cross-section and also along the panel as explained after.

There are two main structural glasses used in engineering, post-processed through tempering with the nominal indicative values of tensile strength as following:

- Heat strengthened Glass (70 MPa)

- Fully Tempered Glass (120 MPa)

It isn't accurate, though, to associate these withstanding stresses with these types of glass since the admissible stress is due to the manufacturing process of these glasses. In fact, even though the stress these glasses can withstand is the same for all, the temperance process for heat strengthened and fully tempered glass imposes the residual stresses mentioned before. The only difference between both these glasses is the temperance level and consequently the value of the existent residual stress.

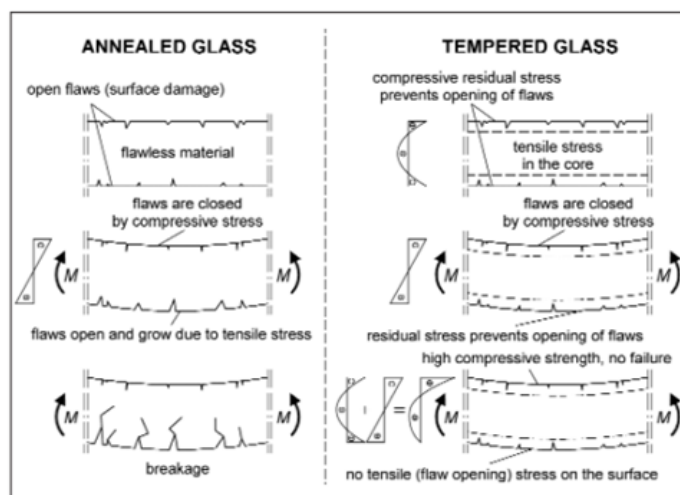


Figure 1-Stresses in annealed and tempered glass[3].

As seen in the picture above, the withstanding stresses are predicted through the following formula:

$$\sigma_{ED} - \sigma_{Res} \leq \sigma_{Rd}; \sigma_{Rd} = 45 \text{ MPa}$$

Eq. 1 - Relation between admissible stress, residual stress and acting stress.

Where  $\sigma_{ED}$  represents the acting stress,  $\sigma_{Res}$  the glass residual stress and  $\sigma_{Rd}$  the admissible stress of the glass.

The idea is to create a residual stress field with tensile stresses in the core of the glass and compressive stresses near the surfaces, since the glass core doesn't contain flaws and offers a good resistance to tensile stress.

Even though fully tempered glass has the best structural performance, it behaves poorly in a post-breakage regime. Still, with the addition of an intermediate layer some post-breakage regime is given to the glass. In the standard case of the models, the intermediate layer will be

SentryGlas. This poor post-breakage behavior is caused by the very small fragments in which it breaks.

With this addition of an intermediate layer the glass is called laminated glass. Lamination is a process in which multiple layers of glass are bonded together to provide redundancy and therefore safety to glass, which by itself, the behavior is hard to predict and breaks without warning.

SentryGlas will be used as the standard material also for the adhesive connection to the glass panel. These materials have in general a very significant variation in Young's Modulus depending on temperature and load duration as seen in the table below. All the models will be considered at standard room temperature of 20° with low load duration.

Young's Modulus $E$ (MPa)		Load Duration						
		1 s	3 s	1 min	1 hr	1 day	1 mo	10 yrs
Temperature	10 °C	692.	681.	651.	597.	553.	499.	448.
	20 °C	628.	612.	567.	493.	428.	330.	256.
	24 °C	581.	561.	505.	416.	327.	217.	129.
	30 °C	442.	413.	324.	178.	148.	34.7	15.9
	40 °C	228.	187.	91.6	27.8	13.6	9.86	8.84
	50 °C	108.	78.8	33.8	12.6	8.45	6.54	6.00
	60 °C	35.3	24.5	10.9	5.10	3.87	3.24	2.91
	70 °C	11.3	8.78	5.64	2.52	1.77	1.44	1.35
	80 °C	4.65	3.96	2.49	0.96	0.75	0.63	0.54

Table 1- Young Modulus in SentryGlas with temperature and load duration variation.



Figure 2-Fracture behavior of annealed, toughened and laminated glass respectively[5].

## 2.2. Connection typology

Stress in glass connections is very relevant because of two main factors. One factor being the decrease in admissible stress of glass at the edges and mostly around holes. Another factor is the stress intensification around these same holes.

Since the entire glass panel has to be designed to the highest stress, the case of bolted connections lead to a problem of oversizing the structure due to the combination of both factors described before.

Because of the incapability of glass to redistribute stress, it's a common norm not to have direct contact between glass and steel or materials with comparable stiffness. In bolted connections there is normally, for example aluminum bushings and injected mortar between the hole and the screw as well as a linear material for the contact with glass. For adhesive connections, rigid or soft adhesives are used to provide a more even distribution of stress.

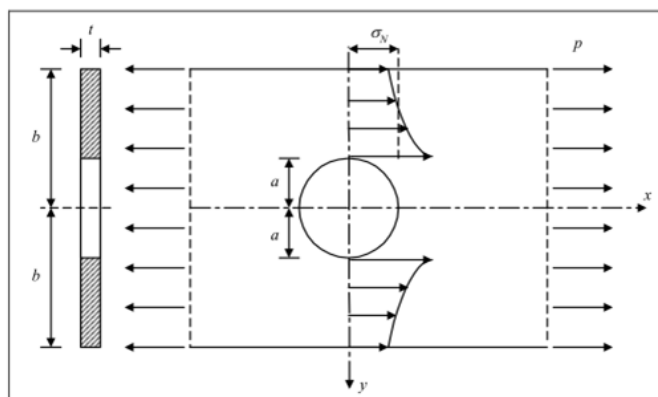


Figure 3-Stress intensification around holes [6]

Regarding connections they can be sub-divided into two classes: mechanical fixings and adhesive connections. The relevant types of connection for this study will be described here and for further information on the ones only mentioned refer to [3].

Both of these supports use normally a 'spider' connected to the beam or other support system which connect four glass panels at the same time. These types of support are in both cases hinged in order not to increase the local stress around the connector.

The following image shows the bolted case support but the application is the same for glued support.



Figure 4 – Spider connector for bolted supports

**Mechanical fixings:**

- Linearly supported;
- Point-clamped supports;
- Bolted- There are a lot of available bolted connections (through-bolt connection, standard countersunk, fully articulated countersunk, partial penetration glass anchor[4]. This type of connection has the overall advantage of being very well studied in different conditions being a safer approach to adhesive connections.

Bolted connection normally have some degrees of movement as seen in the picture below which allow lower stresses in the panel. These degrees of freedom won't be considered in the models since it affects only the stress distribution in panels with acting forces in directions other than out-of-plane which is the case in this study.

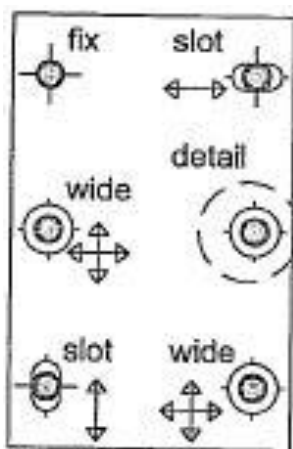


Figure 5 – Allowances of displacement in bolted connections

**Glued supports:**



Only since recently glued supports have been used and mostly used with some redundancy in structures for extra safety since the study under long-term load duration, temperature, UV light and humidity research hasn't been enough developed. Even though it is fairly recent, a lot of adhesives are already available for this purpose:

- Rigid adhesives - Acrylic, epoxy, ionomer adhesives and polyester resin
- Soft adhesives – Structural silicone.

Adhesive connections show a great promise in terms of stress distribution and have the architectural advantage giving the possibility of a smooth surface with the downside of poor high-temperature and moisture behavior.

### 2.3. Variation of stresses in the panel

Even though in tempered and fully tempered glass there are residual stresses which allow stresses in glass, the distribution in the glass panel is not equal across the panel. In terms of residual stress, the panel can be divided in surface, edge, corner and drill hole.

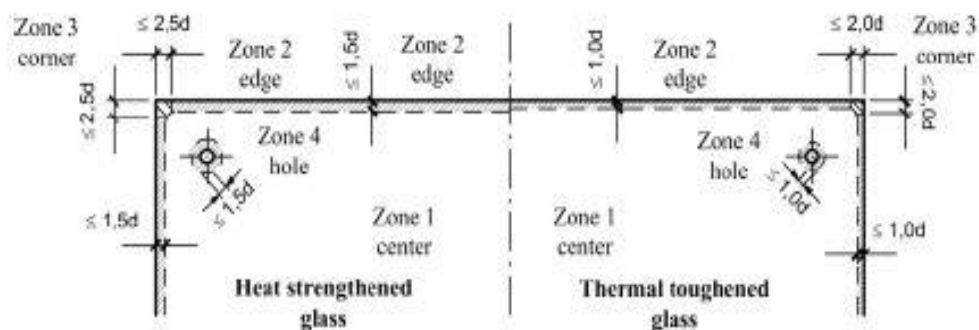


Figure 6 – Distribution of residual stresses across a glass panel[7]

These differences in residual stress will be posteriorly quantified for design proposes.

### 3. Material's properties

For the design and calculation of the models, the material properties of each individual component had to be inputted.

The material's properties for aluminum, stainless steel and glass are known. However the hybrid mortar and SentryGlas properties were assumed based on the values available by the producers and other research. Since, as shown in Table 1, the material's properties vary due to temperature and load duration ([8]), the assumed conditions were 20° and small load duration.

As explained before, the aluminum, SentryGlas and hybrid mortar are used as bushing and interlayer material. Bushing materials are used in order to avoid any direct contact between glass and steel due to the fragile material of the first and poor redistribution of stresses.

In the next chapter further information about the material disposition and geometry will be provided.

For the input in the model the following attributes were considered. All materials were considered with an even distribution of density and with simple elastic behavior corresponding to annealed glass. In the end of the study, as an example, the glass will be pre-designed considering the three cases corresponding to annealed, heat strengthened and fully tempered glass, based solely on the failure stress of each typology. Also for these cases, an analysis in the elastic domain is envisaged since a study beyond the initial failure of glass is not intended.

Properties	Symbol (Unit)	Soda lime silicate glass
Density	$\rho$ (g/mm <sup>3</sup> )	2,50E-03
Young's modulus	E (Mpa)	70000
Poisson's ratio	$\nu$	0,2

Table 2- Properties for glass

Properties	Symbol (unit)	SentryGlas
Density	$\rho$ (g/mm <sup>3</sup> )	1.00E-03
Young's Modulus	E (Mpa)	600
Poisson's ratio	$\nu$	0,45

Table 3- Properties for SentryGlas

Properties	Symbol (unit)	Hybrid Mortar
Density	$\rho$ (g/mm <sup>3</sup> )	1.00E-03
Young's Modulus	E (Mpa)	2780
Poisson's ratio	$\nu$	0,3

Table 4- Properties for hybrid mortar[9]

Properties	Symbol (Unit)	Aluminum
Density	$\rho$ (g/mm <sup>3</sup> )	2,70E-03
Young's modulus	E (Mpa)	70000
Poisson's ratio	$\nu$	0,3

Table 5- Properties for aluminum

Properties	Symbol (Unit)	Stainless Steel
Density	$\rho$ (g/mm <sup>3</sup> )	8,00E-03
Young's modulus	E (Mpa)	200000
Poisson's ratio	$\nu$	0,3

Table 6- Properties for stainless steel

## 4. Definition of glass element and connections in facades

### Facades

In this chapter a parametric analysis will be performed for both bolted and adhesive connections. Both types of connection will have a standard that will be defined posteriorly and different parameters to be changed.

The main results that will be investigated, as referred before, will be the increase in stress around the connections as well as the deformation and stress in the mortar, in the case of bolted connection.

The facade geometry will be  $3000 \times 1500 \text{ mm}^2$  representing a standard glass facade. For both the adhesive and bolted connections the parametric variation will be explained in each section.

The facade will be composed by two glass panels, each with 8mm thickness and an interlayer considered of SentryGlas with a thickness of 1,52 mm.

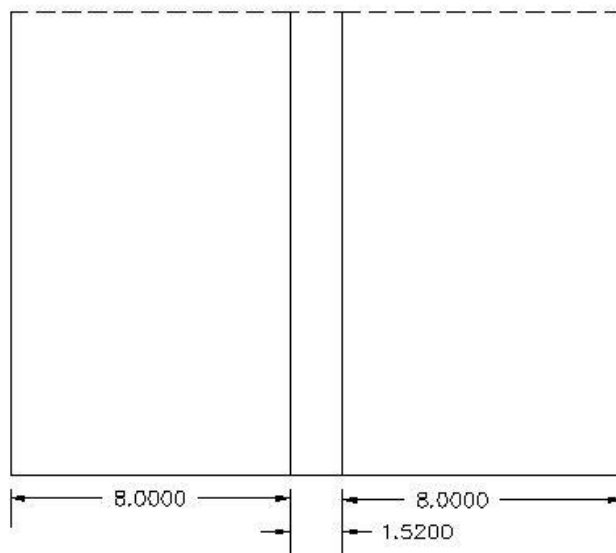


Figure 7 – Lateral view of the facade

SentryGlas was chosen as interlayer since a significant number of investigations with this material are being made. Furthermore, the material's properties are well defined and it has a good creep behavior, which is an advantage in this type of utilization.

The applied load will be an out-of-plane load representing the wind strength with a value of  $2 \text{ KN/m}^2$ .

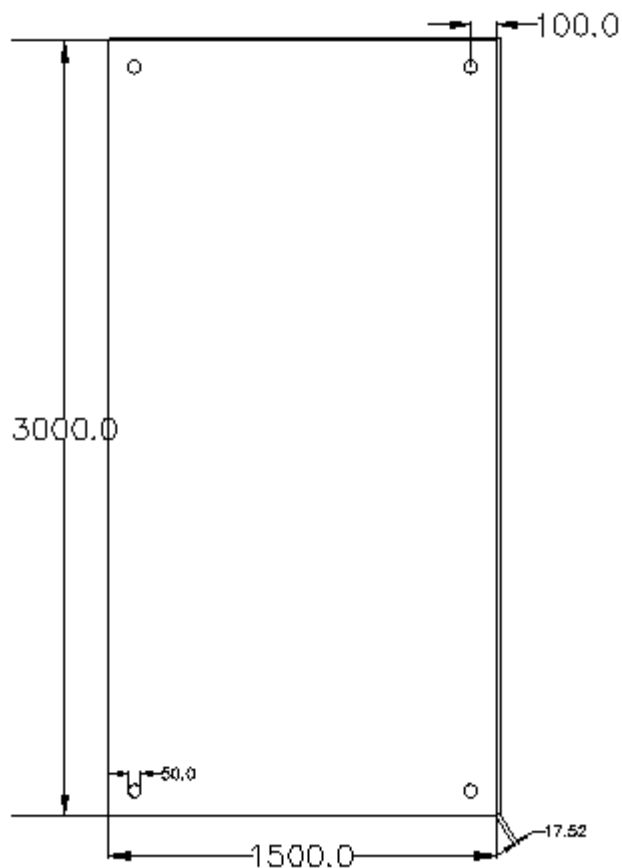


Figure 8 – Standard facade dimensions

#### 4.1. Facade with adhesive connection

The standard geometry for the adhesive connection will be as following:

Description	Units	Value
Distance of hole to edge	H (mm)	100
Diameter of connection	D (mm)	50
Glass panel height	h (mm)	3000
Glass panel width	w (mm)	1500
Glass panel thickness	tg (mm)	8
Interlayer thickness	ti (mm)	1.52
Adhesive connection thickness	ta (mm)	1.52

Table 7 – Geometry of adhesive connection facade

The standard geometry for the facade will be exactly as shown in Figure 8. Other than what is represented in the figure, the connector made with stainless steel will have a thickness of 20mm and will be connected by SentryGlas to the facade. The thickness of the SentryGlas between these two elements will be the same as in the interlayer with 1,52mm thickness in order to redistribute well the stresses imposed. This Sentry Glass layer will have the same behavior to tension as well as compression.

The connector will have 50mm of diameter and a pin with 20mm diameter and 20 mm thickness in order only to better redistribute the stresses in the connector representative of the connection between the connector and the 'spider' in a real structure.

#### **4.2. Facade with bolted connection**

For the facade with bolted connection the geometry will be the same as shown in Figure 8.

The geometry of the bolt will be more complex than the adhesive and so it will be represented in Figure 9 with the components dimensions described below. The standard dimensions were used based on former parametric studies from which the most relevant is present in [9].

In the modelling of this connection type, the parts made from stainless steel are considered as one element since, assuming a proper placement of the bolt, there will be no relative movement between the steel tube and bolt as well as between the steel tube and steel cylinder.

The hybrid mortar and the SentryGlas are used as bushings in order to prevent the contact between steel and glass. The SentryGlas will be used as linear material between the steel cylinder and the glass and will have compression and tension stresses.

The hybrid mortar is injected in the hole, used between the steel tube and the glass and will have solely compression stresses since it's a material that doesn't behave as a glue and wouldn't be strong enough to consider as withstanding the tension stress as a glue between the two elements.

The standard connection will have the following properties:

- Circular hole with 40 mm diameter.
- Steel tube with 5 mm thickness with an outside diameter of 30 mm.
- Injected mortar with 5 mm thickness with an outside diameter of 40mm.
- Steel cylinder with 10mm in height, 30 mm inside diameter and 70 mm outside diameter.
- Linear material with 3 mm in height, inner diameter of 40 mm and outer diameter of 70 mm.
- Washer with 5 mm thickness, inner diameter of 20 mm and outside diameter of 40 mm.

-Nut with 10 mm thickness, 20 mm inner radius and 25 mm outside radius.

The bolt will also continue as shown in Figure 9, past the washer for 10mm in order just to redistribute the stress equivalently through the bolt.

Regarding the bolts it is recommended to use high stress bolts such as 8.8 and 10.9. The sizing of the bolts will be similar as in steel structures. However the bolt connection will have to be oversized in order to have a bigger contact area with the glass and consequently best distribution of stress. We will consider the bolt as 8.8.

For the standard model of bolt we will use an M20 bolt with  $A_s = 245\text{mm}^2$ .

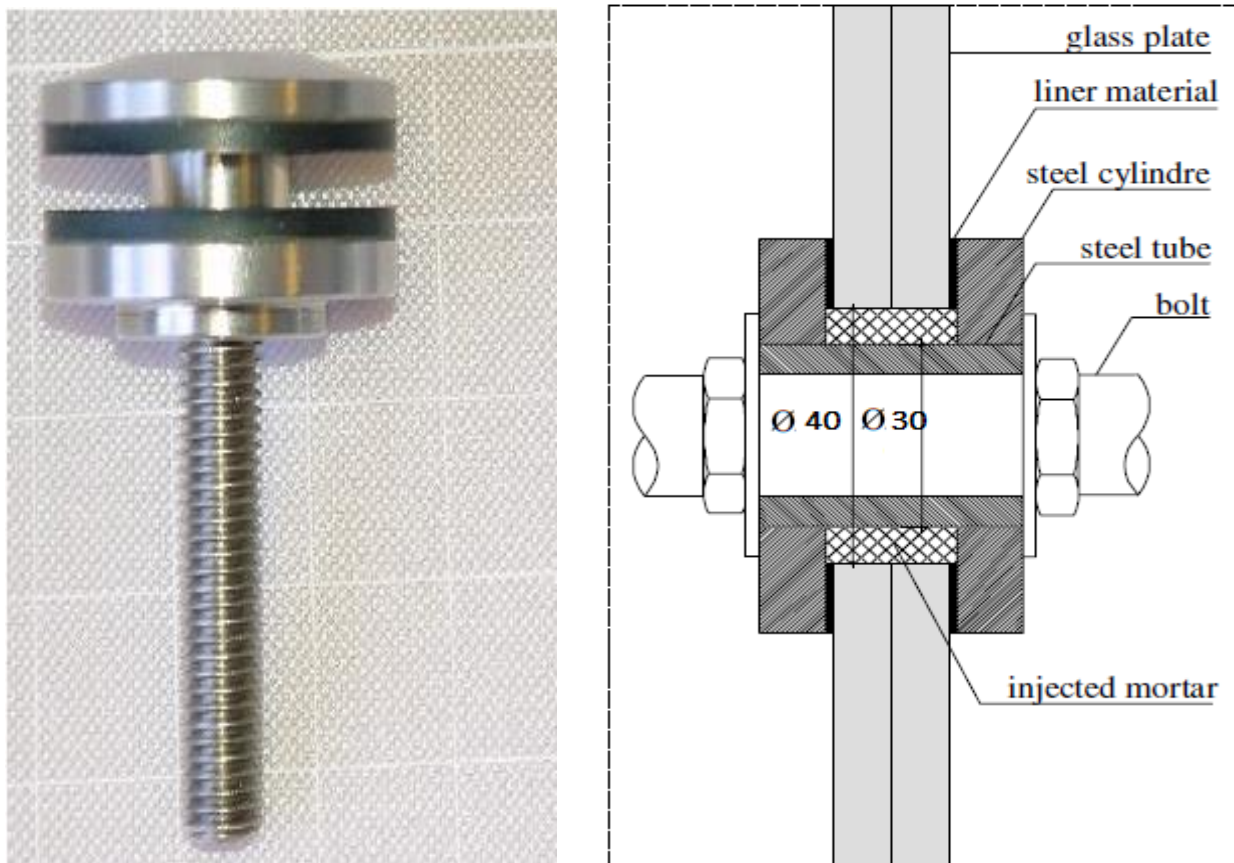


Figure 9-Standard bolt geometry

## **5. Numerical simulation of the study-cases using FEM model**

The aim of this chapter is to establish numerical models on both types of connections.

These models will be calibrated with experimental results and will then be used for a parametric analysis, leading to a complete characterization of the structural behavior of the connections studied in the present dissertation. The code for the numerical analysis is Abaqus.

In this chapter the basic modeling rules used in Abaqus will be described. Some modeling techniques were studied in order to approach an optimized result and some others were considered based on previous studies in the same area. The most important studies considered can be found in [10] and [11].

More specifically, it's going to be explained the interactions between the components, meshing type and dimension used as well as the calculation type used

Due to the quantity of parameters studied, the calculations had to be fast in order to be able to have a good representation of each parameter variation. Because of this reason it's important to make a quality-speed analysis in order to have good results for the limited time of the work.

A problem present in most calculations is the singularities in the model due to the meshing type chosen. These singularities are mostly present in boundary conditions with other components, causing finite elements with infinitesimal dimensions. Because of these finite elements, stresses in these singularities are infinite or non-existent. It is important then to adapt, in some cases, different mesh types from the standard mesh in order to have a realistic distribution of stress.

### **5.1. General numerical tools of facade description**

Both facades with each connection type is symmetrical in the x and y axis and as such, it was used a double plane symmetry axis in order to simplify the calculation time and complexity of the model as seen in Figure 10. To define the boundary conditions it was considered null rotation in 'x' axis and null displacement in 'y' and 'x' for the 'x' symmetry axis and similar to the 'y' axis.



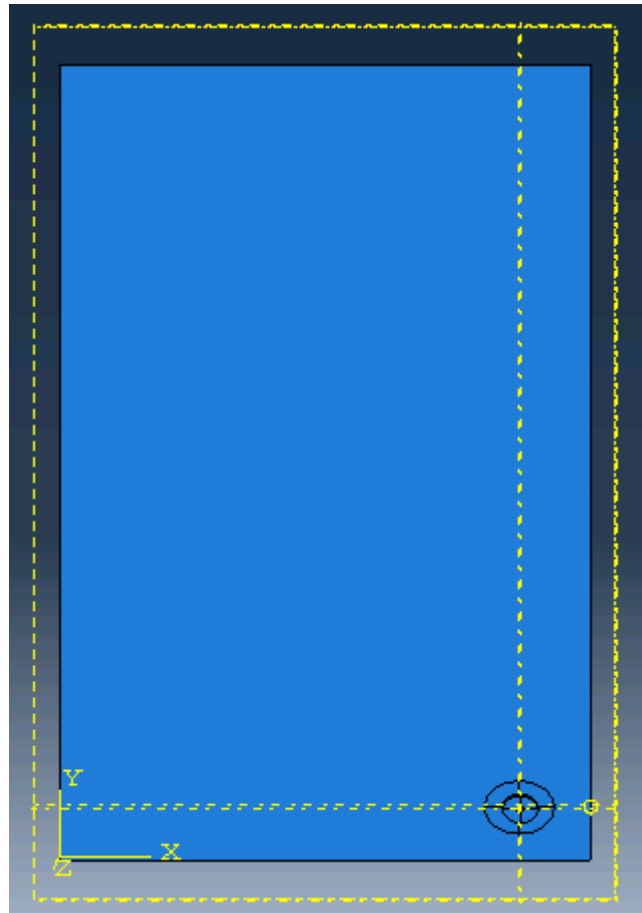


Figure 10 – Double symmetry used in the glass facade

In order to establish the correct mesh leading to converged results, a mesh convergence analysis was conducted.

The mesh discretization's considered are depicted in figure A.

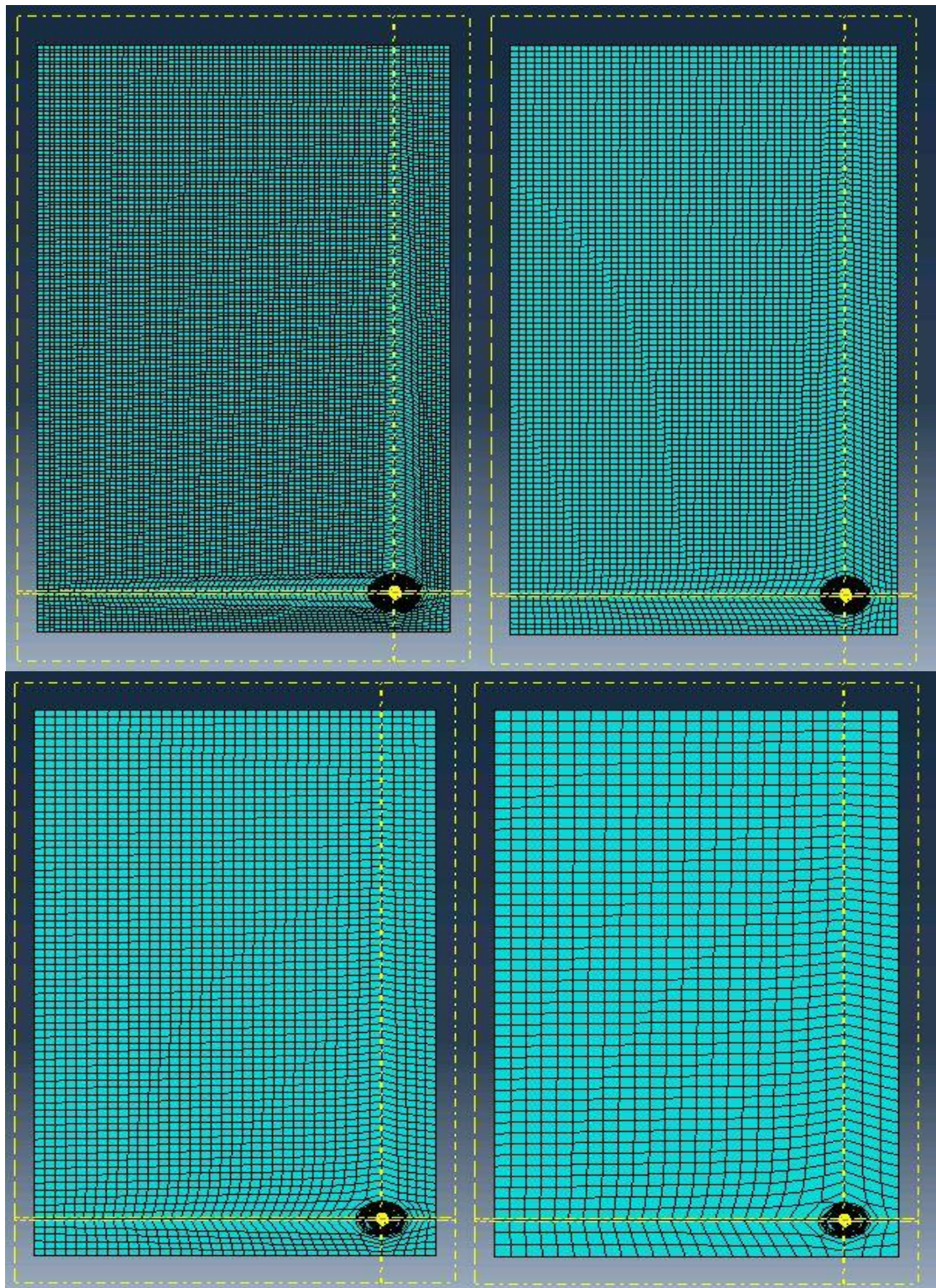
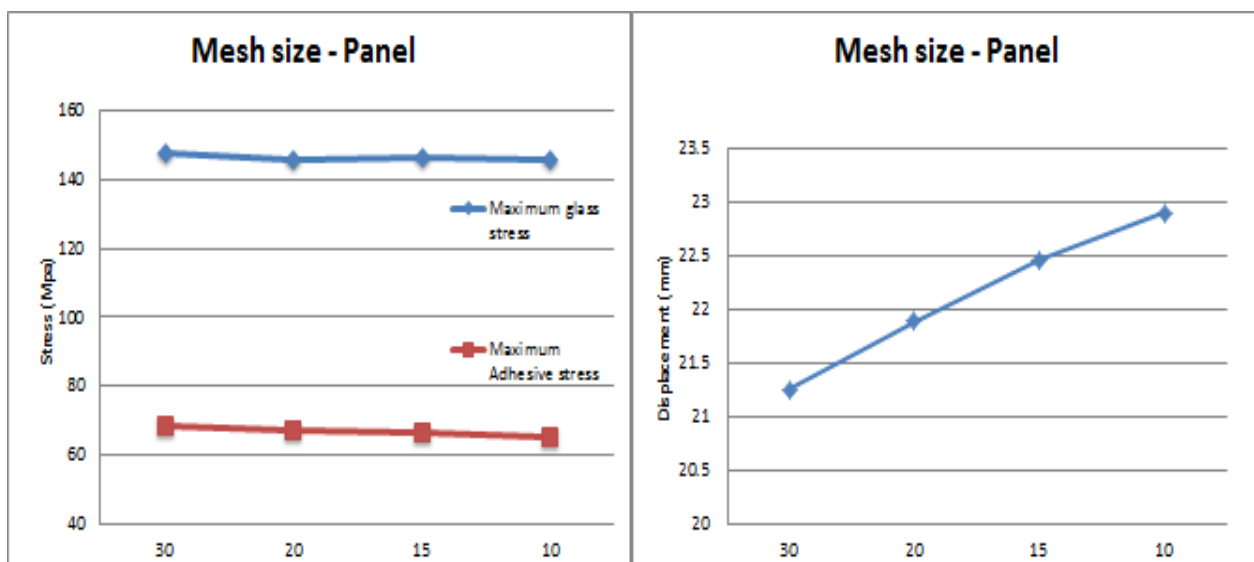


Figure A – From left to right and top to bottom -10 mm, 15 mm, 20 mm and 30 mm.

The comparison between the results of the 4 discretizations was established in terms of variations of the maximum stress in the glass (MPa), the maximum stress in the adhesive (MPa) and the maximum displacement of the glass panel (mm).



Tables 8 and 9 – Values of MGS, MAS and displacement with mesh panel size variation

As seen in the tables 8 and 9, the value of MGS and MAS don't vary a lot with the size of the mesh in the panel and as such, it seems accurate to use a mesh with 20 mm of dimension. The displacement has a bigger variation value but as seen after due to the type of analysis it's not very relevant if the mesh size is consistent throughout the parametric analysis.

Another important factor to have in consideration is the type of analysis of the model and the order of the numerical elements.

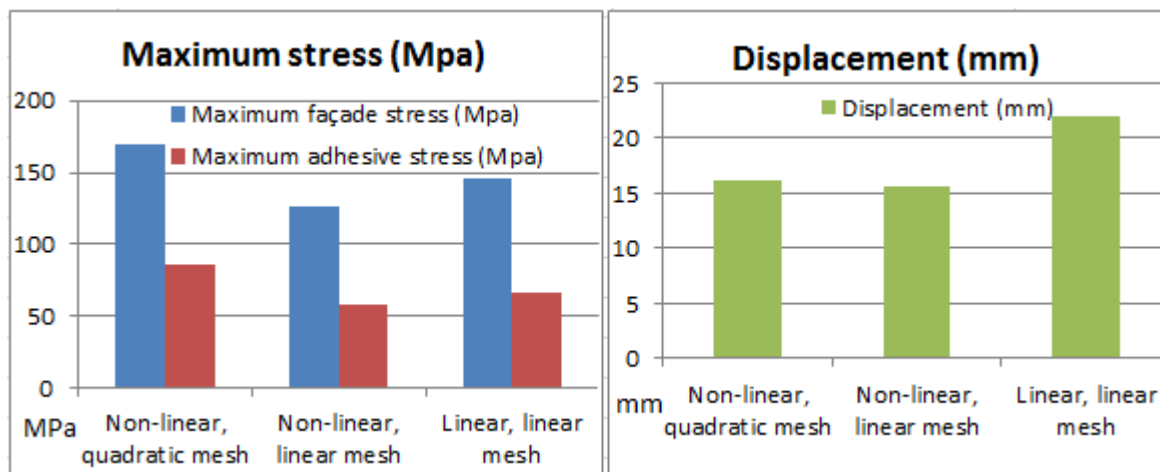
The linear analysis considers the panel to be plane and the material elastic which gives good results in panels with small deformations and material in the elastic domain. When the deformations are no longer infinitesimal and/or the material's properties are non-linear or transient, a non-linear analysis is mandatory. This often is heavier in terms of computational time.

Regarding the type of analysis of the mesh, it can be considered as quadratic, using a quadratic shape function that can better describe the stress and displacement distribution. The linear analysis is much faster but only uses a linear shape function to describe the distribution of strain.



The displacement, as explained after refers always to the maximum displacement of the glass panel, being this located in the center due to the symmetry of the panel, displayed on chapter 6.

All these factors were considered in the tables bellow in order to posteriorly model the facade.



Tables 10 and 11 – Difference in MFS, MAD and displacement with different analysis types.

As seen before there is a significant difference mostly in displacements regarding the analysis type of the model. However, the difference in consumed time was too great between both analysis methods which would not be possible to analyze such an extended parametric evolution as this. The used method for the parametric study was linear for both the analysis type and mesh.

In the end, an early design will be made as an example using the more accurate analysis type – non-linear analysis and quadratic mesh.

As for the meshing type used it is considered more correct by previous authors with similar works ([3];[9]) the use of four-point meshing techniques in panels which in Abaqus can be used using a Hex-dominated mesh. Another mesh type analyzed is a three-point meshing technique named Wedge in Abaqus. These meshing types are studied bellow.

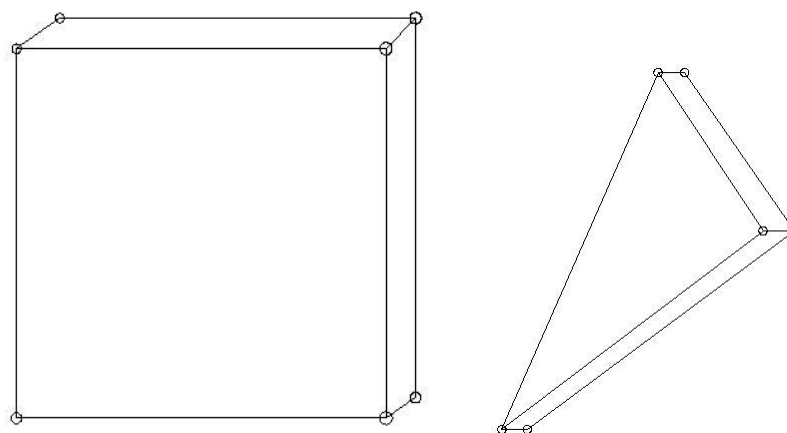
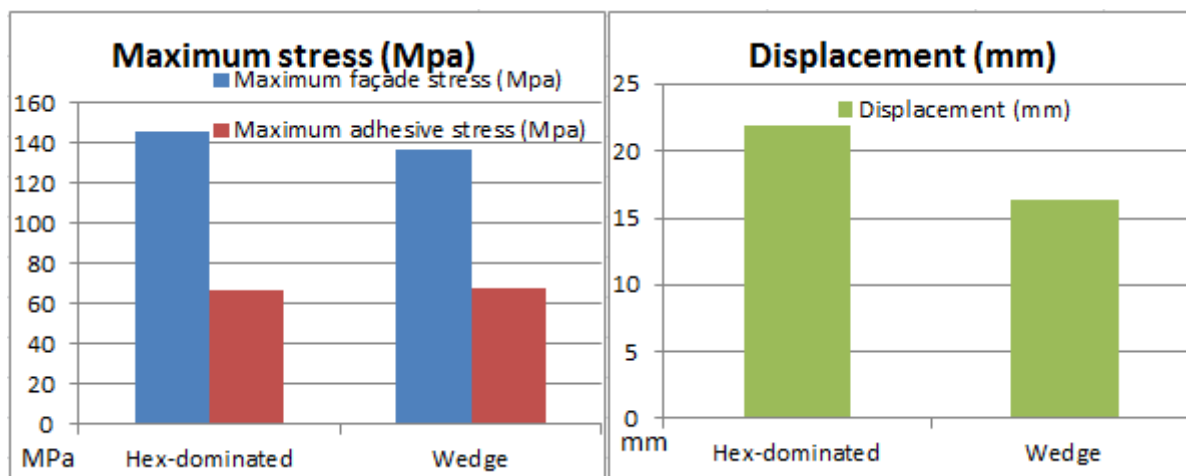


Figure 11 – From left to right – Hex-dominated and Wedge Finite Elements



Tables 12 and 13 - Difference in MFS, MAD and displacement with different meshing types.

Since the hex-dominated mesh type was previously considered to be best, this will be used for the next models. The wedge will still be used but only in the components.

With the meshing type chosen, each glass panel and interlayer was considered to be divided in three through its thickness in order to have a good characterization of stresses as shown in the picture bellow.

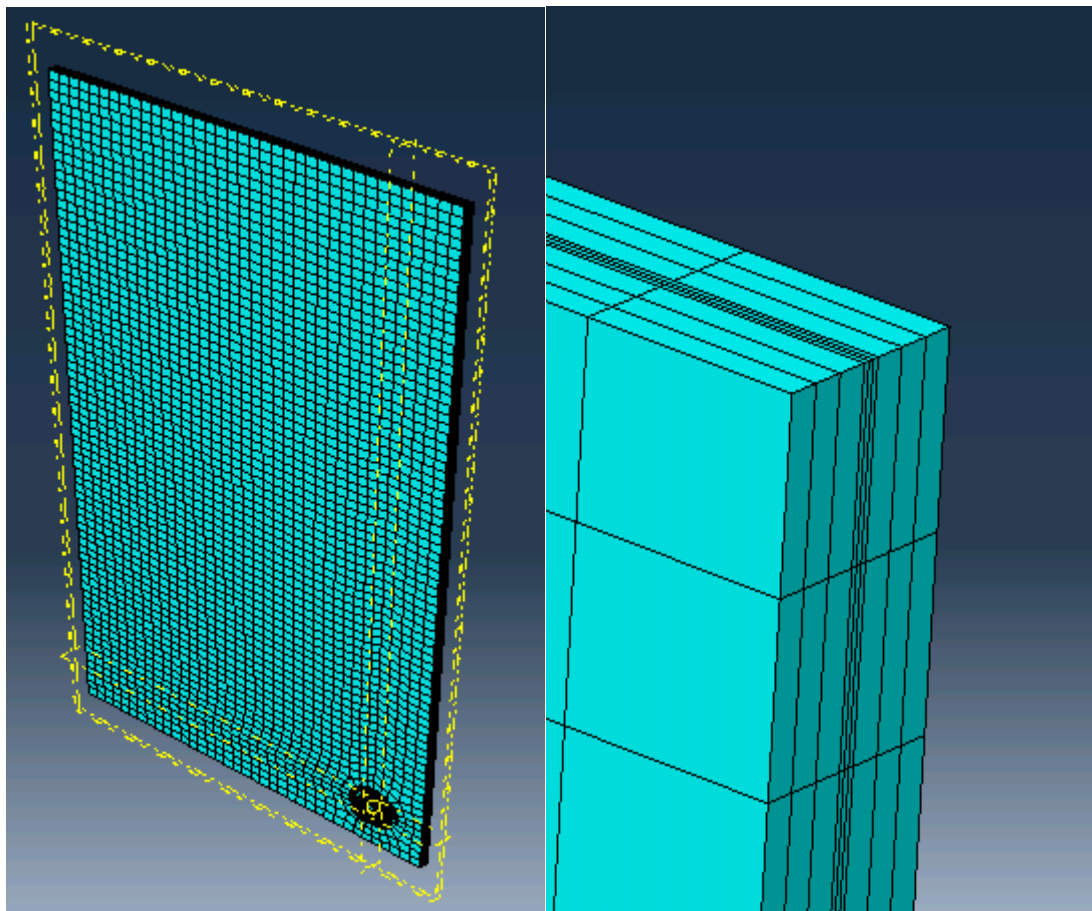


Figure 12 and 13 – Meshing of the glass panels

## 5.2. Numerical model of adhesive connection

According to [B.Siebert [10]], the best results in connection analysis are obtained in circular components when a radial type of meshing is used. Following previous research, this was the method followed, using a wedge meshing type with 3-point elements through the panel with the area of the connector. In order to analyze the best mesh dimension to use, similarly to the analysis done in the mesh dimensions of the panel, a parametric analysis was made with different quantity of mesh elements.

The SentryGlas between the connector and the glass panel is divided in three through its thickness.

The following parametric analysis looks into the ideal discretization of the connector in terms of radial and through thickness elements as shown in the figure below.

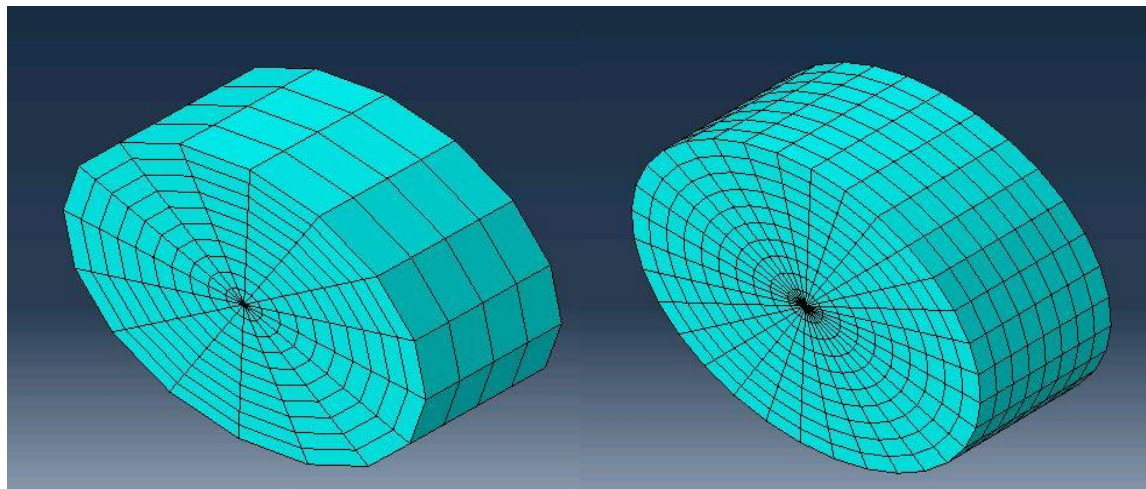


Figure 14 and 15 - 4×4 and 8×8 mesh in adhesive connector.

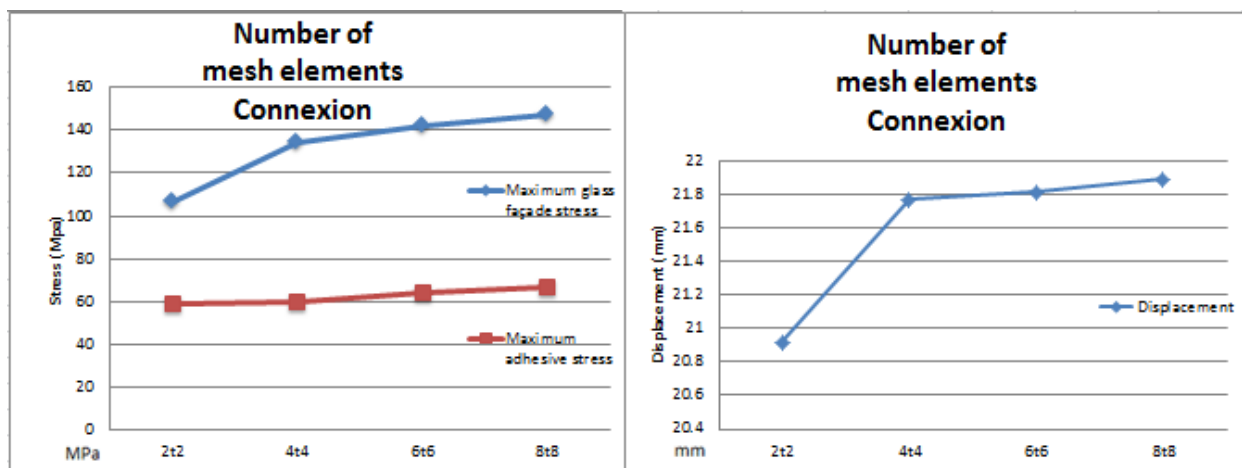


Table 14 and 15 – Stress and displacement analysis with different number of elements.

It is considered from the results of this analysis, that the mesh with 6×6 has a sufficient good result for the analysis and so this will be the standard mesh considered for adhesive connectors.

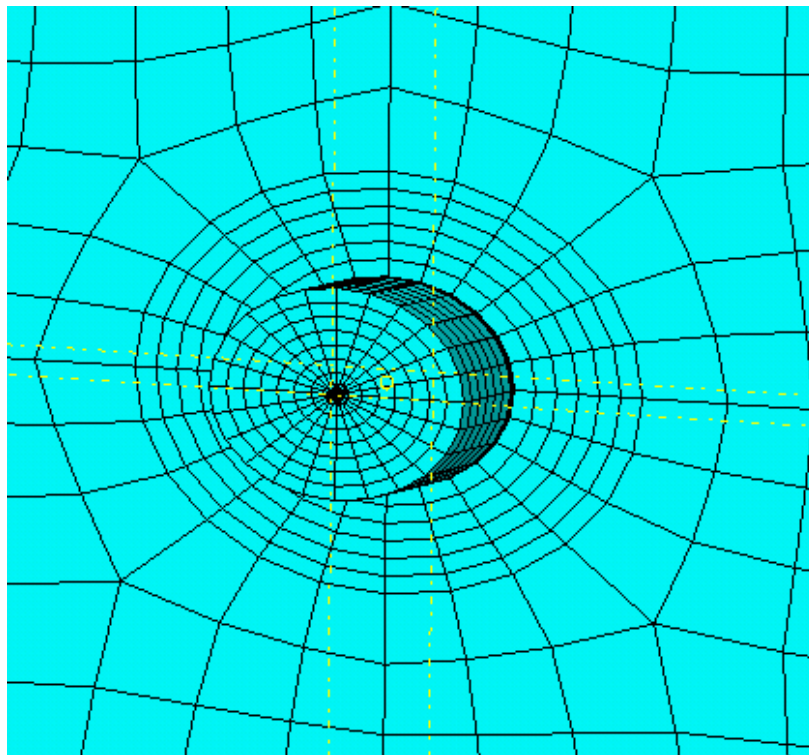


Figure 16 – Final meshing used for adhesive connectors

The interaction between all the components is normal with both tensile and compression stresses transmitted by the glue between the two main components – glass and connector.

The support condition is point-supported with no displacement allowed in the ‘z’ axis and free rotation around every axis.

### **5.3. Numerical model of bolted connection**

For the bolted connection the same assumptions used for the adhesive connection were made, both in terms of number of mesh division and mesh dimension.

The bolted connection was divided into two parts – the bolt (solely a tube with 20 mm diameter) and the rest of the connector with the facade. This division was made in order to establish the border conditions between the two parts in a more realistic manner.

The second part of the connector, like in the adhesive connector, works as a whole and can transmit both tensile and compression stresses due to the SentryGlas to the glass in its surface. The bolt however, being screwed, can only transmit compression stresses in the inner hole, not allowing also the hybrid mortar to transmit tensile stresses in the glass. For this reason, a tie constraint was used in order for these two parts to transmit only compression forces.



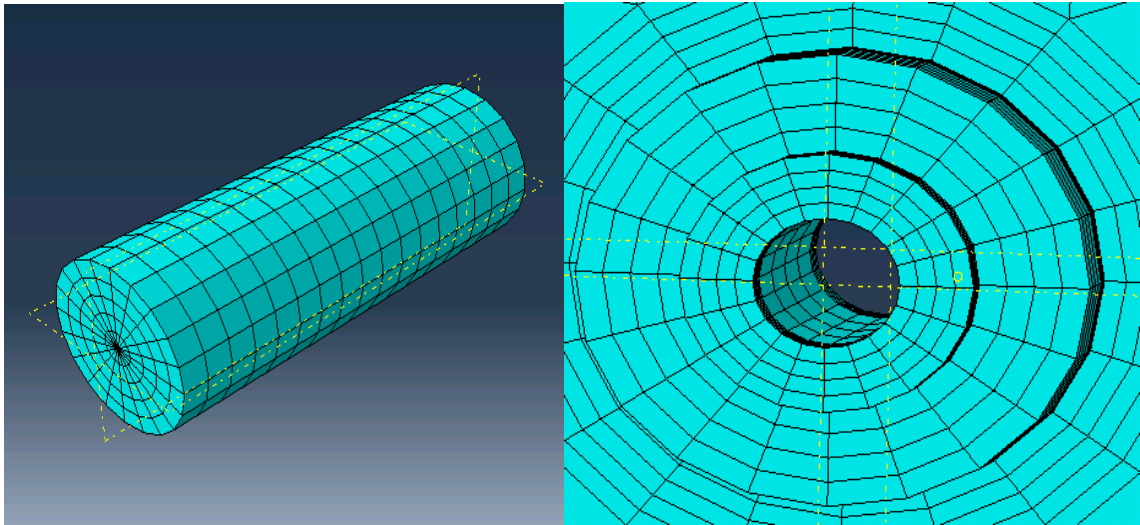


Figure 17 and 18 – Part 1 and 2 of the model with bolted connection

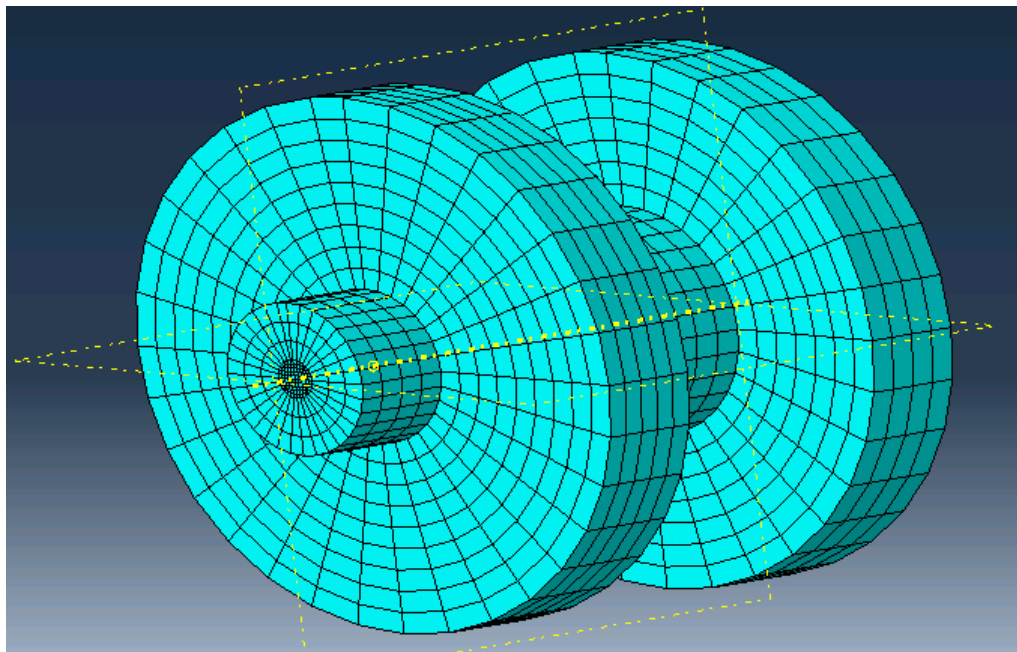


Figure 19 – Bolted connector

The support condition is similar to the adhesive connection with a point-supported tie.

## 6. Parametric analysis of the study-cases

### 6.1. Introduction

In this chapter a parametrical analysis will be made of the various geometrical factors believed to be the most relevant in a glass façade in both connection types. Most of these factors will be similarly studied in both connections and other are specific for each one.

For both cases, the displacement of the glass façade will be studied and, specifically for each connection typology the stresses considered to be more relevant, defined in sub-chapter 6.3.

The objective of this study is to understand the importance of each parameter's variation in order as to decide better and faster the parameters to be used in a practical case of glass design.

### 6.2. Parametrical variation

In this study some of the factors analyzed were considered in both connections which are listed below:

-Parameter H – Distance of the edge of the panel to the center of the connector. This distance will be equal according to the 'x' and 'y' axis. This parameter was chosen due to the different geometries of the 'spider' for both connection typologies and the influence on stress each choice implies.

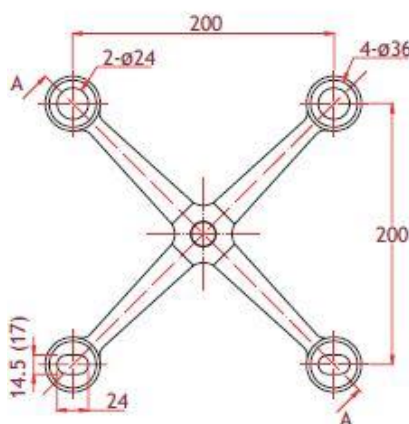


Figure 21 – Example of spider geometry[12]

-Parameter  $h/w$  – Ratio between the height and width of the glass panel. The façade geometry isn't always a factor that engineers can choose due to the architectural project and available geometries in the market. However it plays a big influence on the stresses on glass and is important to be studied.

-Parameter  $t$  – Thickness of the glass panel. This factor is the one most often changed to optimize the structures since it increases the volume for stress distribution and diminishes the stress in the whole panel. It exists in the market in multiples of 2mm but will be studied here with a wider range in order to have a clearer tendency. It's important to assess the influence of this parameter for glass design in comparison with the others.

Specifically for adhesive connection, the studied parameters are listed below:

-Parameter  $D$  – Diameter of the connector. This parameter is one of the most practical to choose in order to reduce the stress concentration around the hole. It has a variety of diameters in the market and needs to be designed having in consideration the maximum stress in the glass as well as in the steel. However the stress in the steel is rarely determinant to its design.

-Parameter  $t_a$  – Thickness of the adhesive. Regarding glass connections, normally, an adhesive product has a given thickness suggestion, from the producer, in order to guarantee a certain minimum behavior in stress. The study of adhesive thickness in direct relation with Young modulus is very relevant due to the impact that it has on stress distribution.

-Parameter  $E$  – Young Modulus of the adhesive. Even though the standard used in this model was SentryGlas for adhesion, there is a variety of adhesives used for this purpose. Among acrylic, epoxy, ionomer adhesives, polyester resin and structural silica there is a wide range of Young Modulus that has a very significant effect in the structural design.

Specifically for bolted connection, the studied parameters are listed below:

-Parameter  $D$  – Diameter of the hole. The variation of this parameter will be made without alteration to the hybrid mortar's thickness, implying only the variation of the diameter of the bolt. It is also one of the most practical parameter to change in order to reduce the concentrated stress, increasing the area in which the stresses can distribute.

-Parameter  $E$  – Young Modulus of the injected mortar. Even though the standard used in this model was the hybrid mortar with the described properties, there is a variety of mortars used for this with a wide range of Young Modulus that has a very big effect in the structural

design. It will be analyzed the Young Modulus of the standard mortar (2780 MPa) and other generic values in order to be able to be applied with more types of mortars.

### 6.3. Procedure and assessment of results

The stresses will be measured both in the glass and in the adhesive. The MGS (Maximum glass stress) will be assessed at the contact surface between the adhesive and the glass. The MAS (Maximum adhesive stress) will be measured in the SentryGlas, in the case of the adhesive connection, and in the hybrid mortar, in case of the bolted connection. These concentrations will be shown in each respective sub-chapter.

The displacement will be assessed at the mid span of the full glass panel. This location corresponds in fact to the edge of the numerical model since the studied part is one-fourth of the real panel due the symmetry according to both axes (Figure 10). The maximum displacement will be shown here since the location and the type of deformation will be equal to both types of connection because of its hinged support.

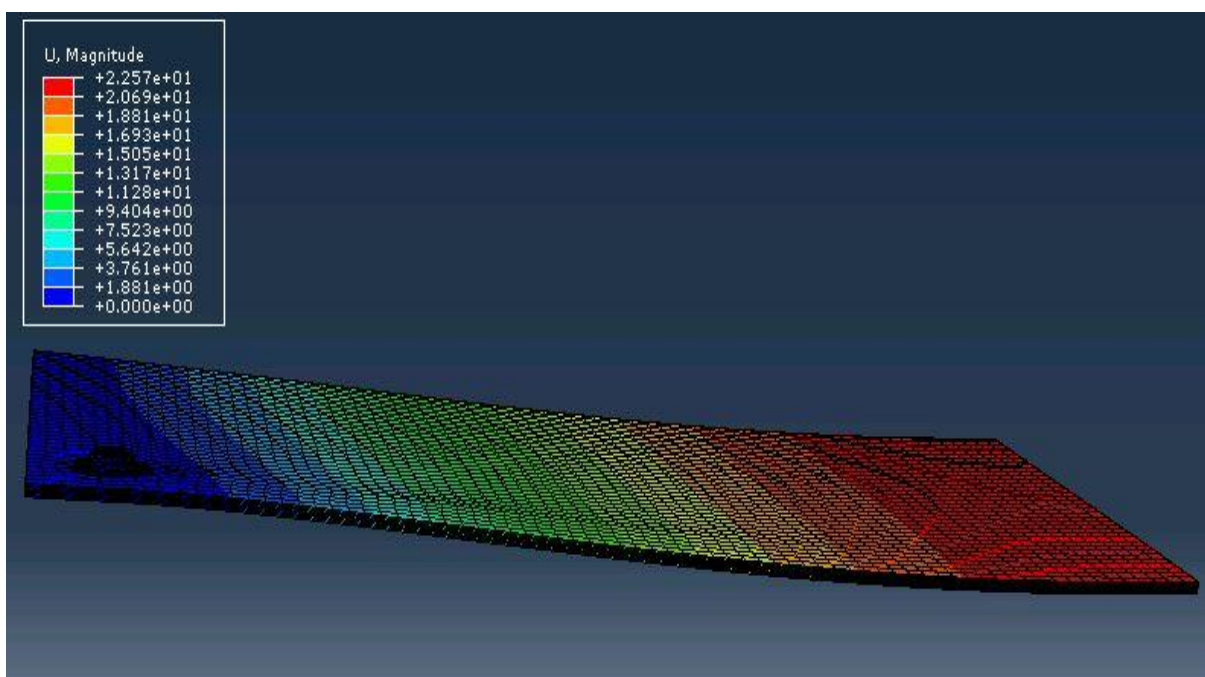


Figure 20 – Displacement of the glass panel

The study was made for both the hinged and non-hinged case in both connection types but the results for the non-hinged connections won't be shown here since it's not relevant for the practical case in which connections are always hinged. As expected the displacements considering the connections hinged are in average 40% higher than with fixed rotation.

### 6.3.1. Adhesive connections

The magnitude and distribution of stresses is shown by the stress contours in the following figures:

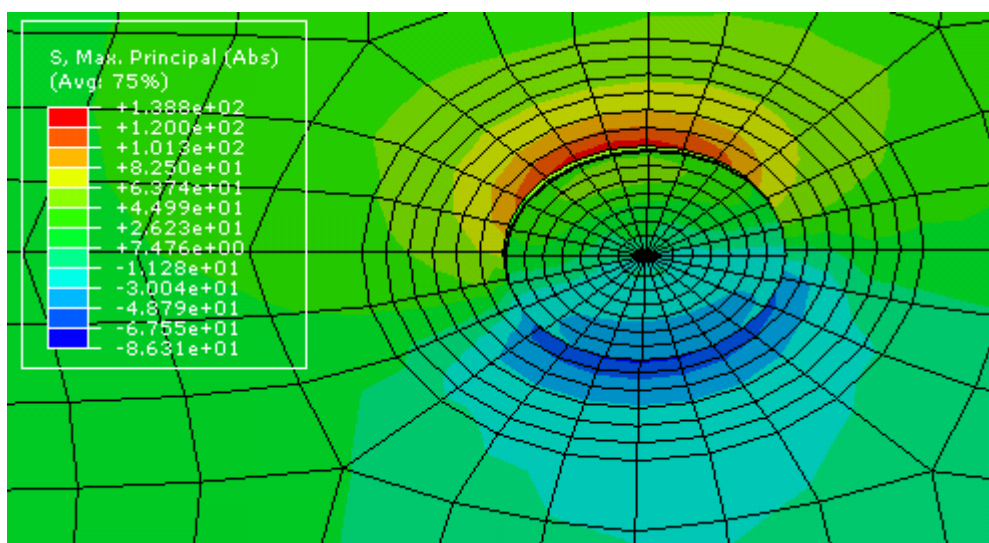


Figure 21 – Stress contours on the adhesive panel around the connector

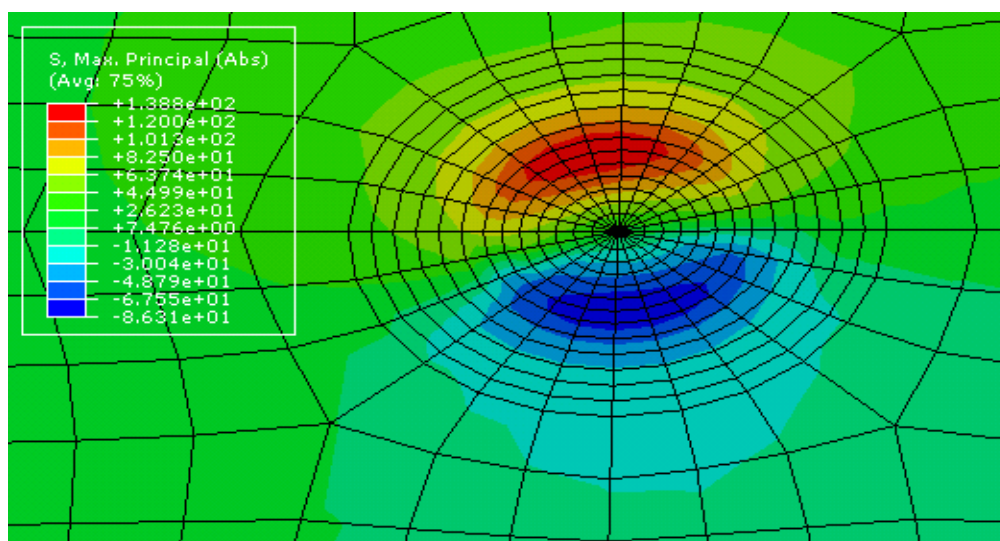


Figure 22 – Stress contours on the adhesive panel around the connector

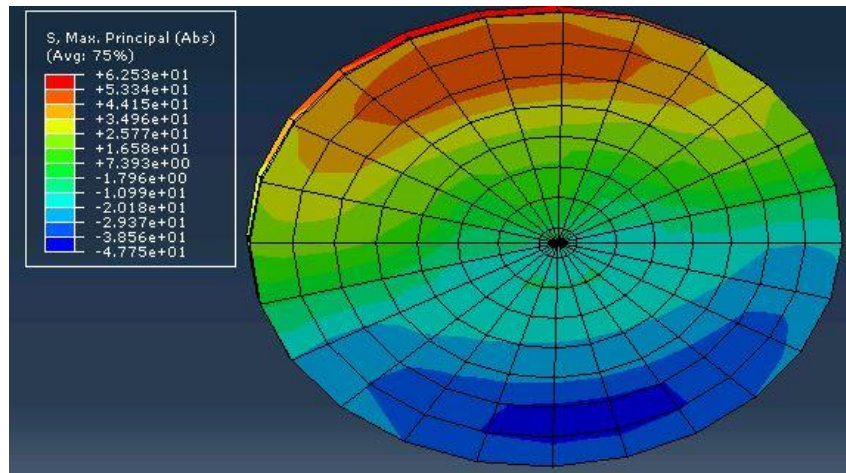


Figure 23 – Stress contours on the adhesive

In the first figure we can see the distribution of stresses around the connector without the connector. In the second figure we see the distribution of stresses in the same area but without both the connector and the adhesive.

The stress in the adhesive is visibly less in the adhesive than in the glass. Even though the form of stress distribution is similar, the stress distribution on the adhesive is much less concentrated and more evenly distributed.

The distribution of stresses around the hole is consistent throughout the rest of parametric studies, varying only the intensity of the stress.

### Study of the parameter H

In this analysis the objective was to study in terms of stress and displacement the importance of the distance of the connector to the edge.



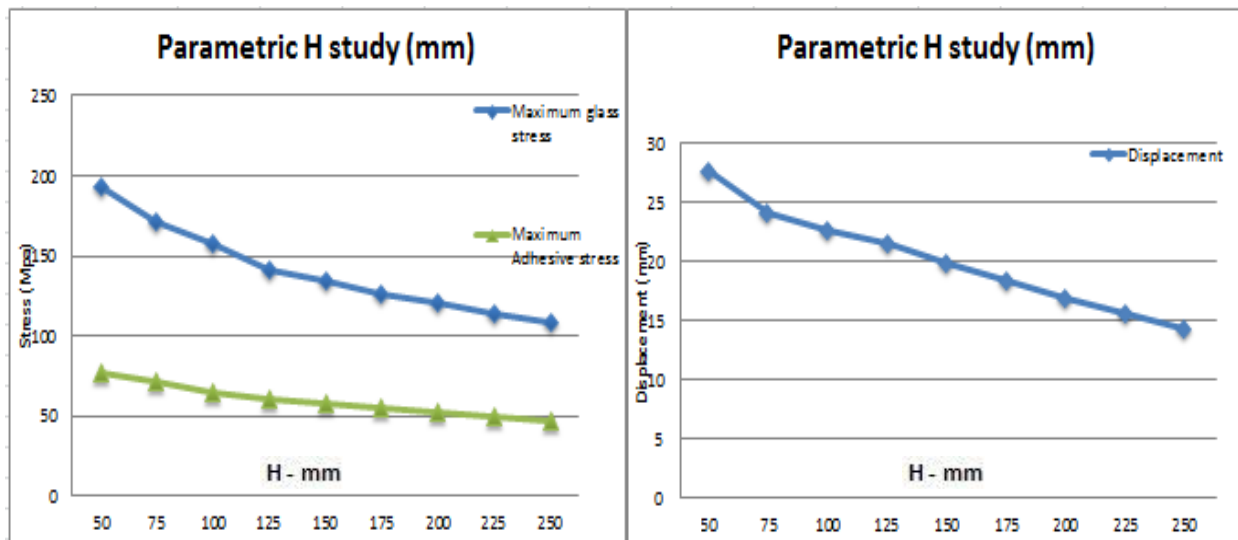


Table 16 and 17 – Study of the parameter H in the adhesive connection

This study shows that for the present connection, the larger the distance hole-edge, the smaller the maximum glass stresses are. The same variation is observed for the maximum adhesive stresses and displacement. The of diminution of stresses decrease at a slower rate as the distance to the hole increases from 12,6% initially to 5,7% in the end. We can assume that the tendency will invert once the connector comes closer to the center but since in practical cases all connectors have a short distance to the edge, bigger distances won't be considered.

### Study of the parameter D

In this analysis the objective was to study in terms of stress and displacement the importance of the diameter of the connector.

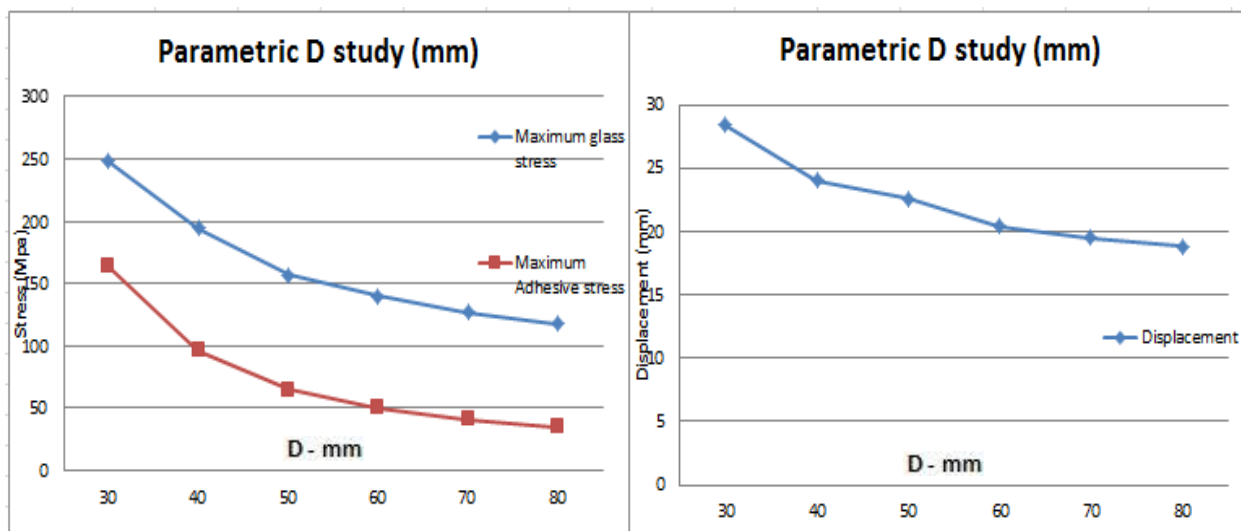


Table 18 and 19 – Study of the parameter D in adhesive connection

In this study, the progression of maximum stresses decreases with the same tendency as the previous analysis with the parameter H. The stresses decrease from 27,7% with a diameter of 30mm to 7,8% with a diameter of 80mm. The same behavior is observed in the case of the displacement.

### Study of the parameter h/w

For this parameter study the intention is to describe the behavior of different types of facade formats other than the reference one. The standard dimensions of the facade are 3000 mm × 1500 mm implying an h/w value of 2.

In order to be able to compare the maximum stresses and displacements, the area of the facade has to be constant since the applied force has to be equal for a direct comparison.



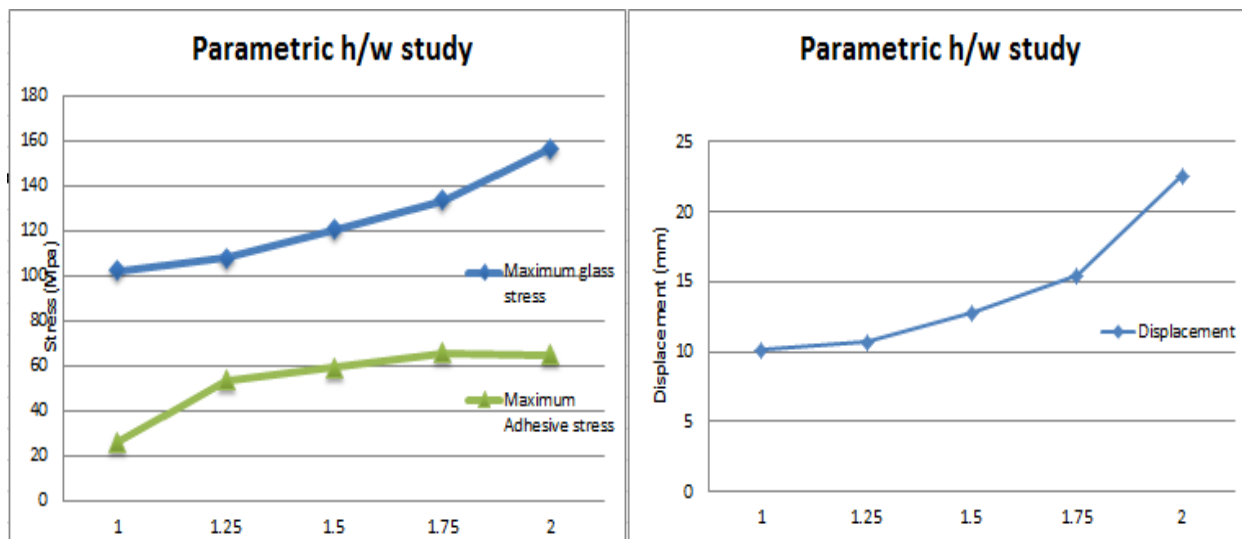


Table 20 and 21 – Study of the parameter h/w in adhesive connection

This study shows that a drift from the squared geometry in the facade panel, leads to a higher concentration of stresses. In this case, choosing the reference facade used would increase in 53% the stress concentration in the glass.

### Study of the parameter E (Young Modulus)

In this study it will be analyzed the Young Modulus of SentryGlas (600 MPa) among other generic values. The generic values considered are analyzed in order to be able consider a broader range of adhesives.

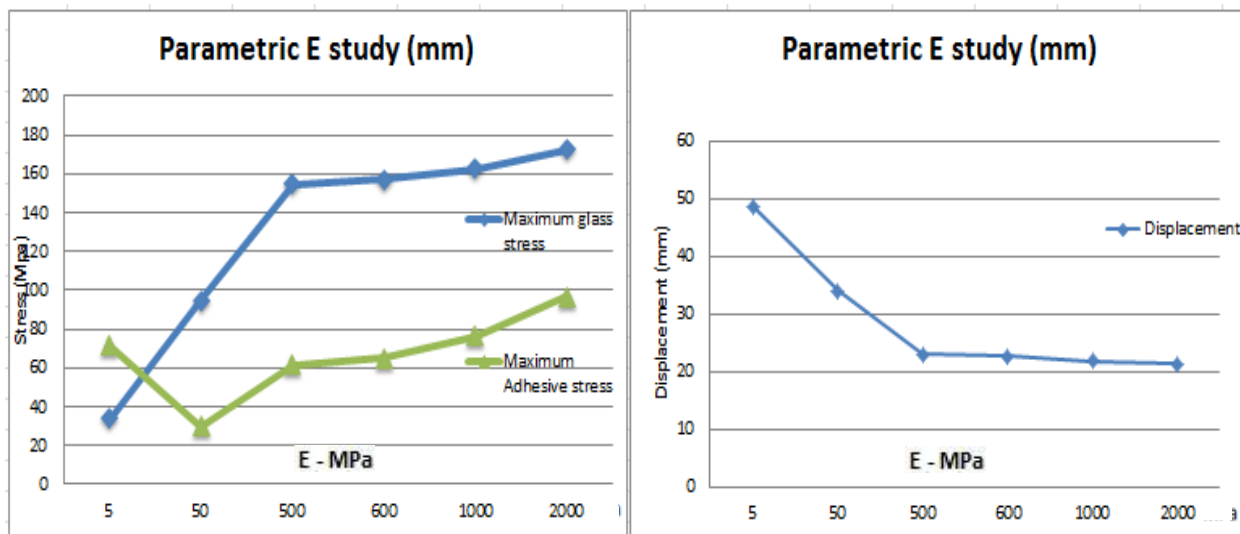


Table 22 and 23 – Study of the parameter E in adhesive connection

This study shows how the variation in Young Modulus of the adhesive can reduce the concentrated stress around the surface area of the connector. The difference in values of E were too big for the graph to be in scale but it's possible to see that it has a linear tendency.

The displacement has an opposite tendency because the more soft and deformable the adhesive becomes the smoother the stress distribution is and the bigger the deformation and rotation of the connector are.

Even though there aren't any adhesives with 5 MPa it's clear to see the influence of choosing between a rigid and a soft adhesive in the design of the structure.

### Study of the parameter $t_a$ (Adhesive thickness)

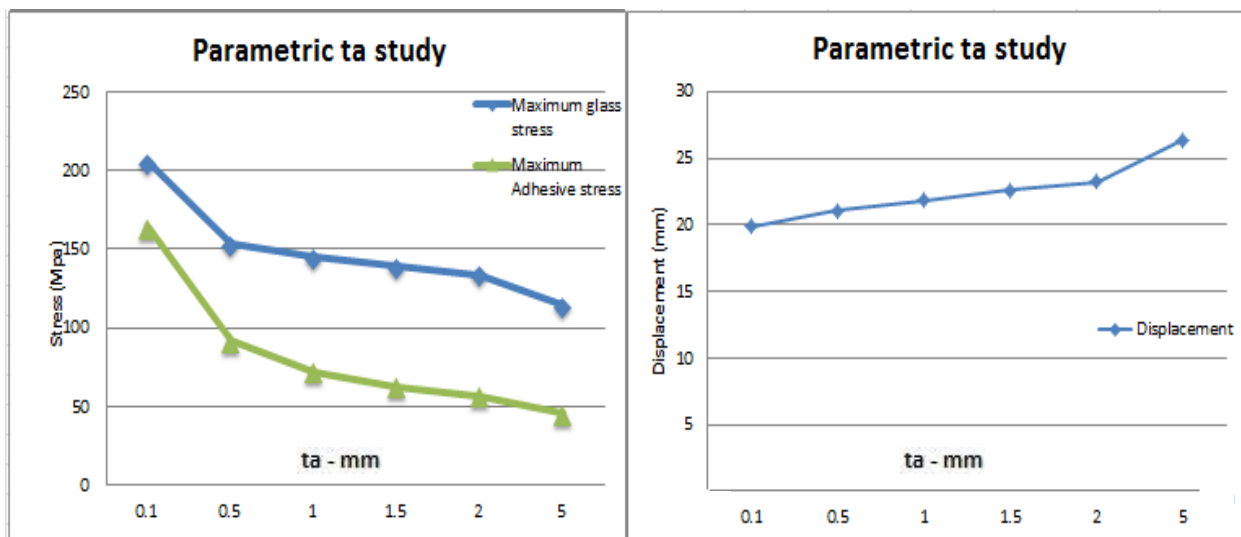


Table 24 and 25 – Study of the parameter  $t_a$  in adhesive connection

This study shows how the variation in thickness of adhesive can have a great impact on the stress. The behavior in both stress and displacement is linear and similar to the behavior with E variation.

### Study of the parameter $t$ (Glass panel thickness)

The choice of the thickness of the glass for design is bound by the stresses around the connector since this is the location for the higher stresses. Because of this, the glass is normally oversized with other more economical choices for diminishing the stress.

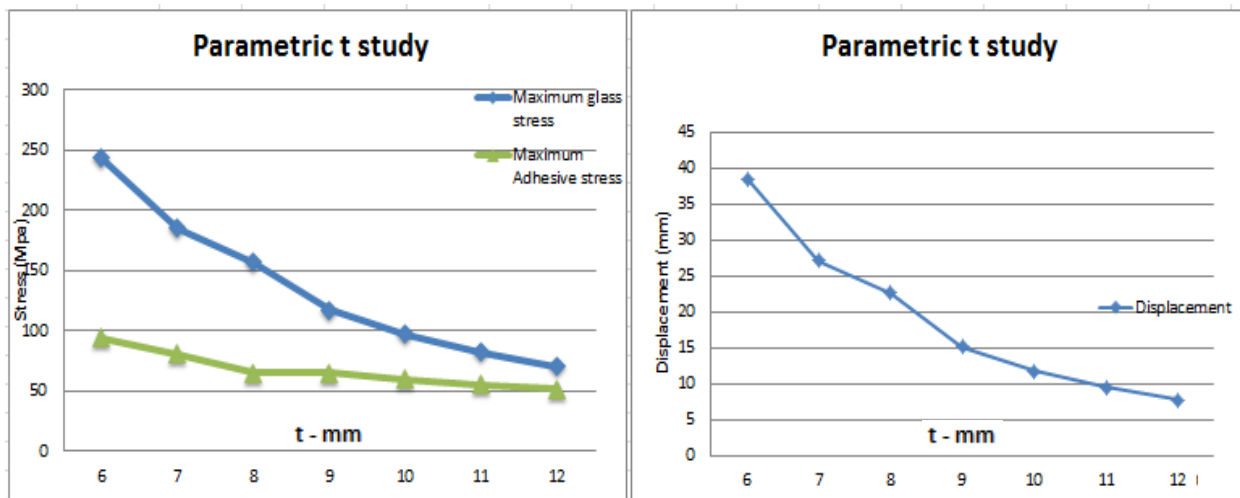


Table 26 and 27 – Study of the parameter t in adhesive connection

The displacement follows the same exponential behavior as other factors with a decrease in stress of 31,4% with a thickness of glass panel of 6 mm to 17% with 12 mm.

### 6.3.2. Bolted Connections

The location and form of the located stress in this connection type will be shown in the figures below:

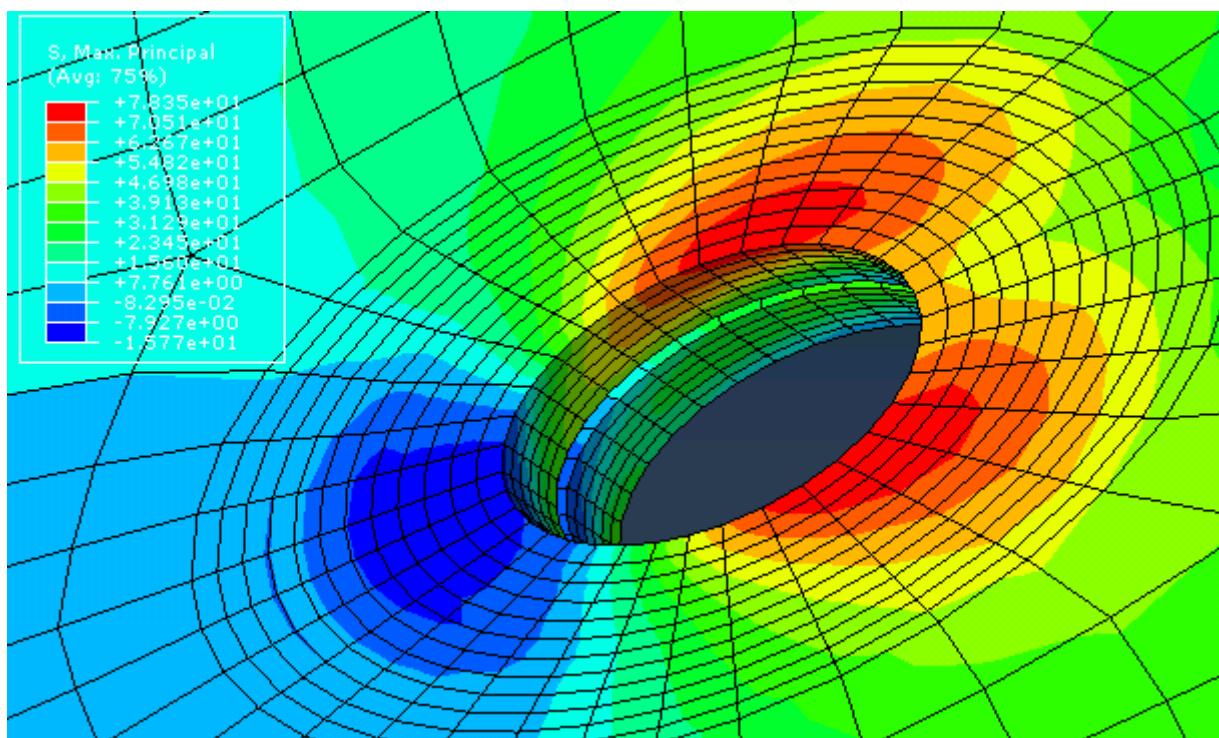


Figure 24 – Stress distribution on the glass panel around the hole

The picture shows only the glass panel without the mortar, adhesive and bolt. The stresses are transmitted in two ways. One is in the surface of the glass in the area of the steel cylinder in a similar way of the adhesive connector with tensile and compressive forces being distributed in the area. Other is by contact in the hole, allowing only compression forces to be transmitted to the mortar by the bolt.

In these studies the values of both maximum and minimum stresses in the glass, as well as the values of maximum stresses in the mortar and maximum displacement will be analyzed.

The maximum and minimum stresses will be located, as seen in the figure above, around the hole. The minimum mortar stresses will be always negative due to the properties of the contact with only compression forces transmitted. The displacement will be assessed, like in the adhesive connection, in the middle of the glass panel.

### Study of the parameter H

In this analysis the objective was to study in terms of stress and displacement the importance of the distance of the connector to the edge.

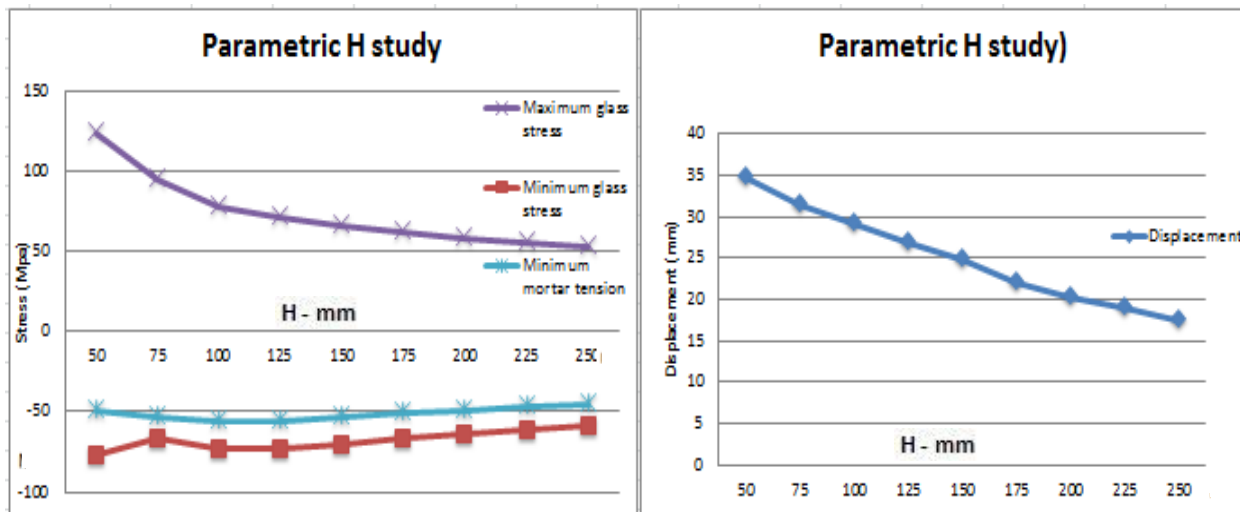


Table 28 and 29 – Study of the parameter H in bolted connection

This study shows that for the present connection, like for the adhesive one, the stresses diminish at a slower rate as the distance to the hole increases from 31,3% initially to 5,6% in the end. We can assume that the tendency will also invert once the connector comes closer to the center. The same behavior is observed in displacement.

### Study of the parameter D

In this analysis the objective was to study in terms of stress and displacement the importance of the diameter of the hole. It's important to note that the diameter corresponds to the diameter of the hole and not the bolt. Since the dimensions of the steel cylinder and mortar don't change, the diameter of the bolt will be 20 mm less than the hole.

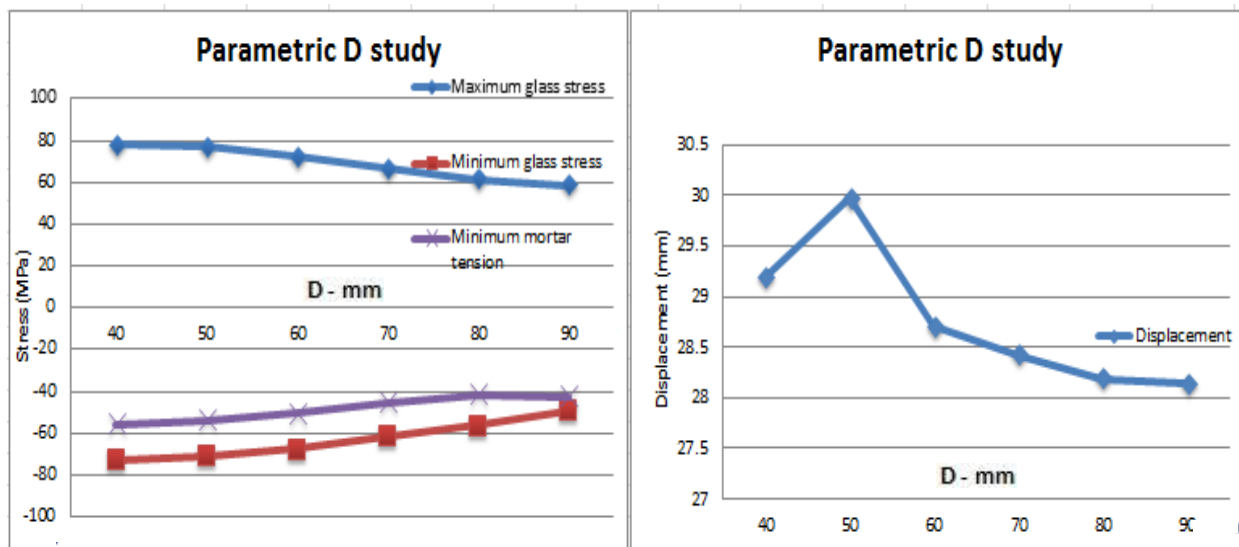


Table 30 and 31 – Study of the parameter D in bolted connection

In this study, the progression of maximum stresses decreases with a different tendency as in the adhesive connection. The stresses decrease from 1,5% with a diameter of 40mm to 5,5% with a diameter of 90mm. In terms of displacement the behavior is exponential with a value that is probably due to an anomaly is the mesh with a diameter of 50 mm .

### Study of the parameter h/w

For this parameter study the intention is to describe the behavior of different types of facade formats besides the standard one, with different geometries as for the adhesive connection.

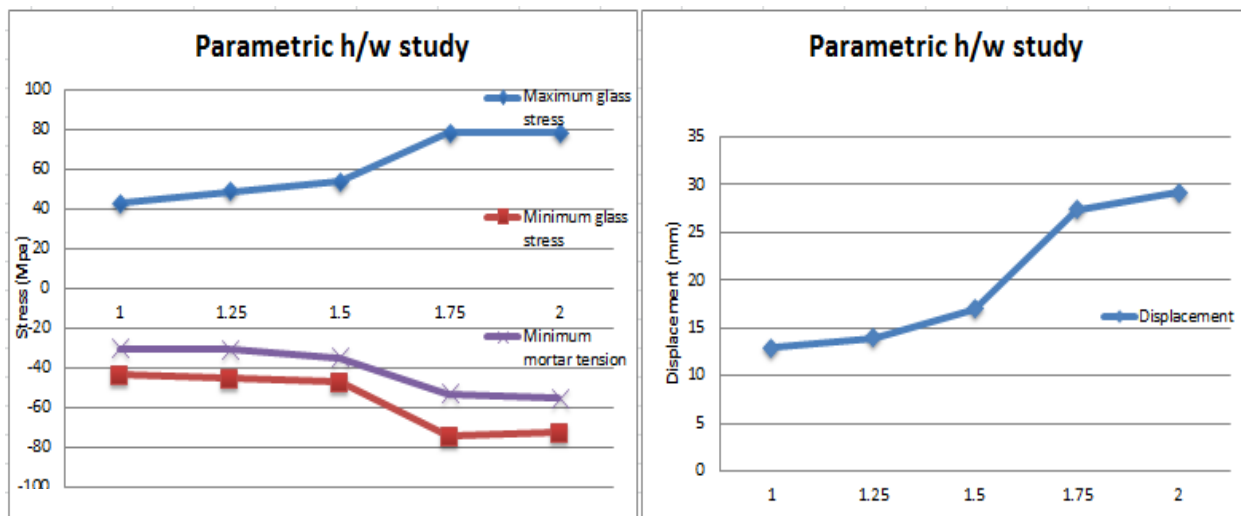


Table 32 and 33 – Study of the parameter h/w in bolted connection

This study shows that an augment in eccentricity of the facade leads to a higher concentration of stresses. In this case, choosing the standard facade used would increase in 82,5% the stress concentration in the glass, more than for the adhesive connection.

### Study of the stiffness of mortar E (Young Modulus)

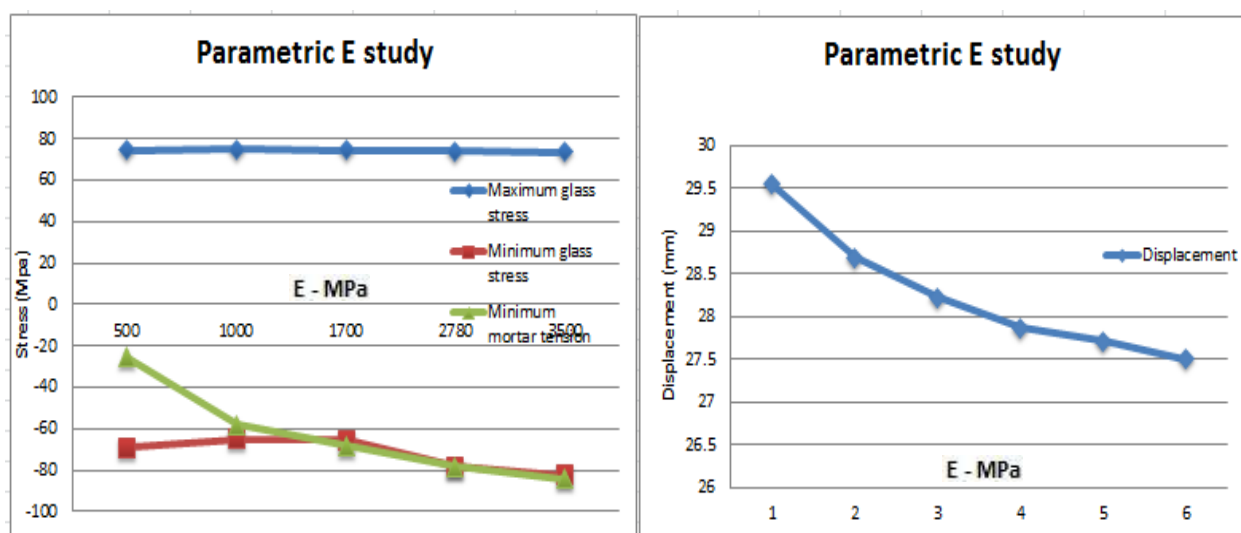


Table 34 and 35 – Study of the parameter E in bolted connection

This study shows how the variation in Young Modulus of the mortar alters the distribution of stress around the edge of the hole.



The maximum stresses don't change because the tension stresses are being applied only in the surface area of the glass by means of the steel cylinder through the linear material. Regarding the minimum stresses, the softer the mortar is, the more deformation exists and better is the distribution of compressive stresses inside the hole.

The displacement has an inverted tendency because as the mortar becomes more soft and deformable, better the stresses are distributed but bigger is also the deformation and rotation of the connector.

In the case of bolted connection in comparison with adhesive connection, the influence of the Young Modulus is much smaller.

### Study of the parameter t (Glass panel thickness)

For this parameter study the intention is to describe the behavior of different thickness of glass panels similarly to adhesive connections.

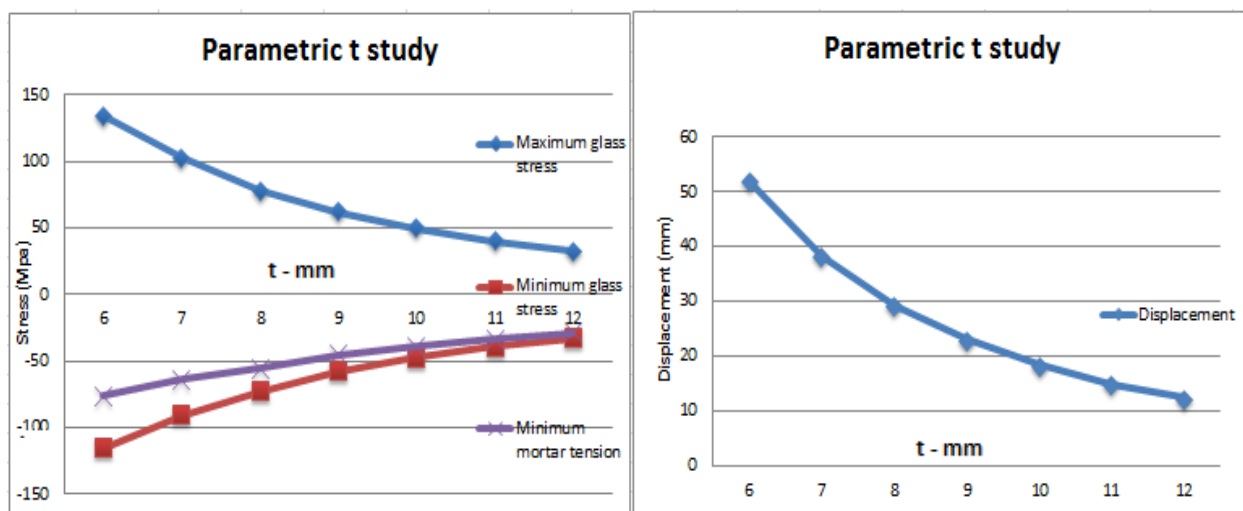


Table 36 and 37 – Study of the parameter t in adhesive connection

The displacement follows the same exponential behavior as other factors with a decrease in stress of 30,7% in maximum stress with a thickness of glass panel of 6 mm to 23,5% with 12 mm.

## 7. Conclusions of the parametric analysis

### 7.1. Conclusions of the parametric tests

In this section, the conclusions taken from the previous chapter are summarized. It's difficult to establish a general solution for every early glass design and even the tables prepared will not exclude the designer from having to run models in order to attain the optimal solution. However, with the referred tables it's possible to narrow down the values of a certain parameter in order not to wonder extensively into combinations of parameters and to have a faster iteration to the desired value.

In the continuation of this chapter, an example of early design will be made for both bolted and adhesive connections in order to clarify the use of the parametric tables.

In the previous tables we can consider in each parameter, though subjectively, the value from which increasing becomes less effective. These values are purely qualitative and must have an economy background in order to correctly design the element.

#### **-Parameter H**

This parameter is not in most cases a choice since it's dependable on the format of the 'spider' which dimensions aren't normally in the designer's choice. Because of this fact and the logarithmic format of the curve which makes the increase in distance edge/hole progressively less relevant for the stress, an  $H=100\text{mm}$  seems to be a good compromise in both cases.

#### **-Parameter D**

In the adhesive connection 40 mm and 50 mm are a regular value to choose even though it isn't a clear value in the graphs for the same reason of parameter H. For the bolted connection a good option would be between a hole of 40 mm with a M20 bolt until a hole of 50 mm with a M30 bolt.

#### **-Parameter h/w**

With this parameter the preference is clearly a square facade with an  $h/w$  equal to 1.

#### **-Parameter E**

In the adhesive connection the preference is clearly the softest adhesive. However other problems occur with over-deformation, failure stress and other factor common to all adhesives like temperature, moisture and resistance over time

In bolted connections, since the value E of the mortar mostly only affects minimum stresses, the E of the standard hybrid mortar for our case (2780MPa) is a good compromise.

**-Parameter  $t_a$**

This variation of this parameter, related directly with the parameter E has the same problems.

Even though the best choice for minimum stresses would be the thickest layer of adhesive, the failure stresses would be much lower. In order to change this parameter from the value advised from each supplier, specific research with adhesives has to be made.

**-Parameter t**

This parameter will vary only with different loads. It has to be adopted for each specific case.

## **7.2. Comparison of bolted and adhesive connections with different E**

In this section we will compare the stresses in both types of connections. It's not possible though to make a direct comparison between both types of connections since both have their advantages and disadvantages.

Adhesive connections have the advantage of having a great potential in stress distribution with the evolution of the studies about different adhesives. However these studies are still in the beginning phase and behavior to temperature, moisture and duration of loading is still not very well studied.

Bolted connections are better studied but are limited in terms of architecture, diminution of stress and manual work due to the mandatory drill and complex setting; furthermore the uncertainty around holes is critical for rupture.

This next parametric comparison is meant to show the possibilities in terms of only stress concentration of adhesive connections and bolted ones. This table shows a parametric study of the standard bolted connection and two adhesive connections with two different Young Modulus of 1000 and 10 with variation of distance to the edge.

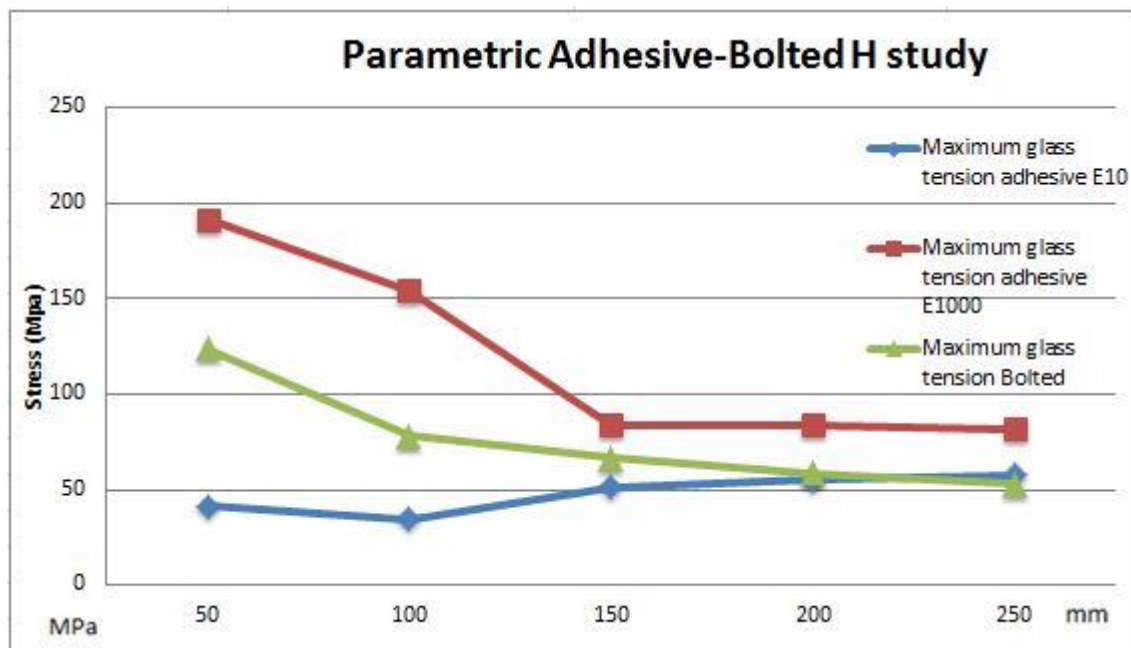


Table 38 – Comparison of bolted and adhesive connections

The two adhesives behave in an opposite manner with the change of the parameter H. This behavior depends on the E of the adhesive and it's assumed that with a certain E between the two presented, the stresses would be unchanged with variation of H.

With this study we can see how adhesive connections can have a better or worse stress distribution depending on the Young Modulus of the adhesive.

### 7.3. Design of the case study using bolted and adhesive connections

In order to better understand the early design stage of a glass façade, an example will be made resorting to previous research on residual stresses in a glass panel. It's very relevant the consideration of different residual stresses along the panel with more information on chapter 2.3. More research about the subject can be found in [7];[13];[9].

For this example it will be used solely the fore mentioned research on residual stress across the panel and on FEM models. These models will be analyzed with non-linearity due to the large deformations of the panel.

In order to be able to analyze the parts separately without any interference of pre-stress profiles between two zones of the glass, the distance from edge to hole has to be less than 3 times the thickness of the glass. This interference occurs when two different zones with different formats for residual stresses are too close.

For each glass panel with  $t=10\text{mm}$  the total thickness is  $21,5\text{ mm}$  and the minimum distance is  $64,5\text{ mm}$ . This distance only applies to bolted connections.

Zone	Plate loadbearing		Panel loadbearing	
	Heat strengthened glass	Thermally toughened glass	Heat strengthened glass	Thermally toughened glass
1) surface	-30	-84	-30	-84
2) edge	-43	-75	-45	-63
3) corner	0	0	0	0
4) drill hole	-40	-68	-37	-57

Table 39 – Residual stress values in different plate zones

The complete design would have to be made accordingly with the European norm [prEN 13474-1, 3] and the German [E DIN V 18008-1,-2] based on the concept of partial security factors which would be given to each zone (Figure 6). Due to the irregularities in the hole, the security factor would be bigger in that zone. These security factors won't be applied since this example only includes an early design.

With the relation of stresses in glass we obtain the maximum value of stress around the hole:

$$\sigma_{ED} - \sigma_{Res} \leq \sigma_{Rd}; \sigma_{Rd} = 45 \text{ MPa}$$

Bolted connection, residual stress around the hole:

$$\sigma_{Res} = 37 \text{ MPa}; \sigma_{ED} \leq 82 \text{ MPa}$$

Adhesive connection, residual stress on surface:

$$\sigma_{Res} = 30 \text{ MPa}; \sigma_{ED} \leq 74 \text{ MPa}$$

The case will be designed only for the stress concentration in the connectors since the stresses on the edges, corners and other surfaces are much smaller.

The iterative process to reach the desired stresses for each respective type of connection will start with the standard case and change from case to case.

#### **Adhesive connection:**

Considering at first the reference connection, the stress concentration appears to be too high. The Adhesive 2 is the standard connection with a thickness of glass ( $t$ ) of  $10\text{ mm}$ . Since it still doesn't respect the criteria, the diameter is changed in Adhesive 3 to  $60\text{ mm}$ .

Adhesive connection	Maximum glass tension	Displacement	Maximum Adhesive tension
Standard	126	15,6	58,52
Adhesive 2	77,4	8,4	56,20
Adhesive 3	70,7	7,8	44,83

Table 49 – Non-linear analysis on different adhesive solutions

Since  $70,7 \leq 74 \text{ MPa}$ , the maximum stress is respected.

**Bolted connection:**

Considering at first the standard connection, the stress concentration appears to be too low and the structure seems to be oversized. Since smaller diameters weren't included in this research and the thickness of the glass can't be diminished or it wouldn't respect the maximum stress, the chosen standard solution will be chosen.

Bolted connection	Minimum glass tension	Displacement	Maximum Mortar tension
Standard	66.25	20.08	-71.25

Table 41 – Non-linear analysis on bolted solution

## 8. Creep test

### 8.1. Introduction

Adhesive point-fixed supports and embedded adhesive connections have been the subject of intense investigation due to their capacity of stress distribution. The reason of its importance was in part shown in the previous chapters. However, due to some still little investigated factors like behavior in high temperatures and long term behavior these connection types have still to be used with some ambiguity in real facades with different support systems to complement the adhesive connections.

The purpose of this second part of the thesis is to analyze the behavior of two different adhesives: TSSA (Transparent Structural Silicone Adhesive) and SG (SentryGlas). The TSSA has a great potential in adhesive connections because of its low Young Modulus, high transparency, good mechanical performance and weather behavior. In the previous chapters we can see the importance of this factor in the distribution of stress in a glass panel.

In this part of the thesis an experimental creep analysis will be conducted on three different sample types under loading under the effect of temperature (50°) in order to observe their long-term behavior in comparison to the effect of loading without temperature.

### 8.2. Definition of the samples and procedures

Three different types of samples were tested, directly given by the supplier:

	GP height - h (mm)	GP width - w (mm)	GC diameter - D (mm)	Sample thickness - t (mm)
SGE	300	150	40	25
SGC	300	150	40	19
TSSAC	150	150	40	15

Table 42 – Definition of the sample's geometry

The SGE (SentryGlas Embedded) sample is composed by 3 layers of annealed glass with dimensions of 6+10+6 mm with an interlayer of 1,5 mm.

The TSSAC (TSSA Centered) sample is a monolithic glass panel with 16 mm thickness.

The SGC (SentryGlas Centered) sample is a monolithic glass panel, tempered with 19mm thickness.

The procedure of assembling the samples included:

- Calibration of the LVDTs.
- Placement of aluminum stripes in the support both up and down of the samples in order not to have direct contact with the steel from the supports.
- Development of a mechanism to keep the samples in place in case of failure.
- Calibration of the LVDT creep registration program.
- Mounting of the specimens with special care to being completely centered in the supports.
- Placement of the LVDTs with a range of 2cm but started around the range of 0,5cn in order to have more correct results.
- Placement of the charges and loading (Figure 26 and 27).

In the table below is described the loading used for each sample:

Specimens	LVDT's numbers	Weights (kg)	Loading (KN)
SGE 1	0;2	35,9	3,52
SGE 2	12;13	16,19	1,59
SGE 3	16;17	71,58	7,01
SGC 1	3;4	80,54	7,89
SGC 2	5;6	35,62	3,49
SGC 3	8;9	16,19	1,59
TSSAC 1	14;15	49	4,80
TSSAC 2	18;19	35,52	3,48
TSSAC 3	20;21	16,22	1,59

Table 43 – Loading in the specimens

The geometry for the SGC specimen and load application is present in the figure below. For the other specimens, the distance of support and application of the load is similar with the only difference of each panel's geometry.



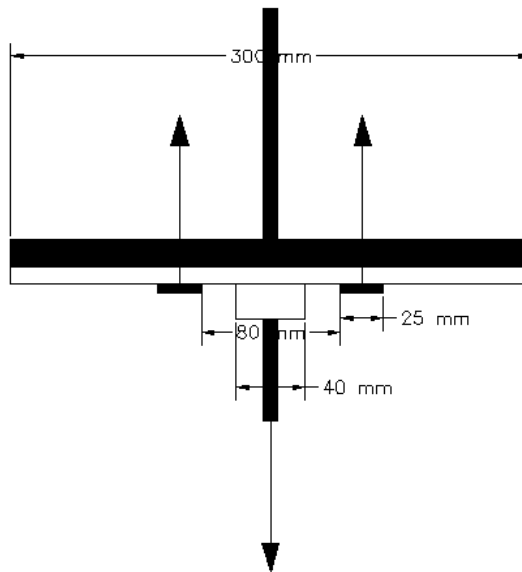


Figure 25 – Geometry of the sample SGC

In the next pictures we can see the mechanism which was used to load the specimens, the charges used and the samples.

The mechanism uses an arm which distance is 10 times from the support to the charges than from to support to the samples. In this way charging the samples with 10 times the actual weight used.

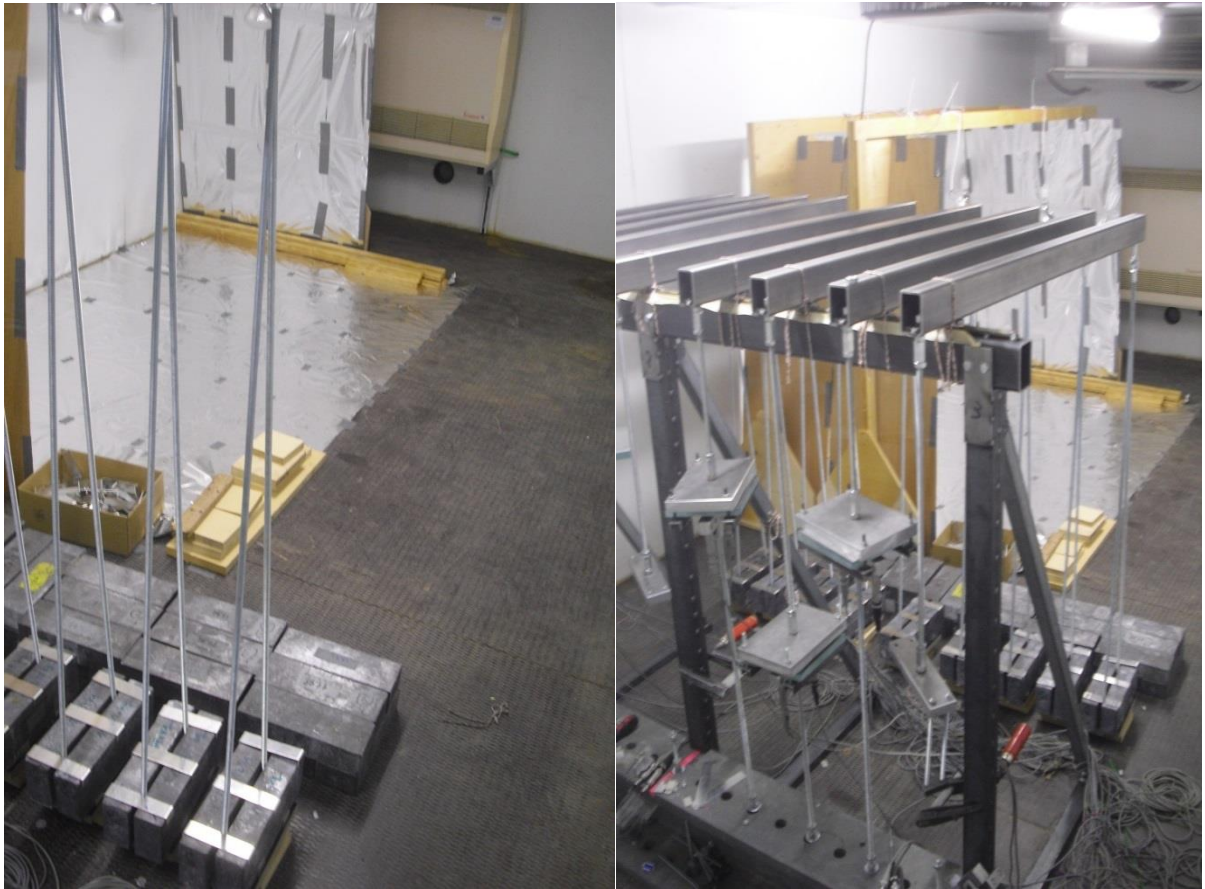


Figure 26 and 27 – Placement of the charges and loading mechanism

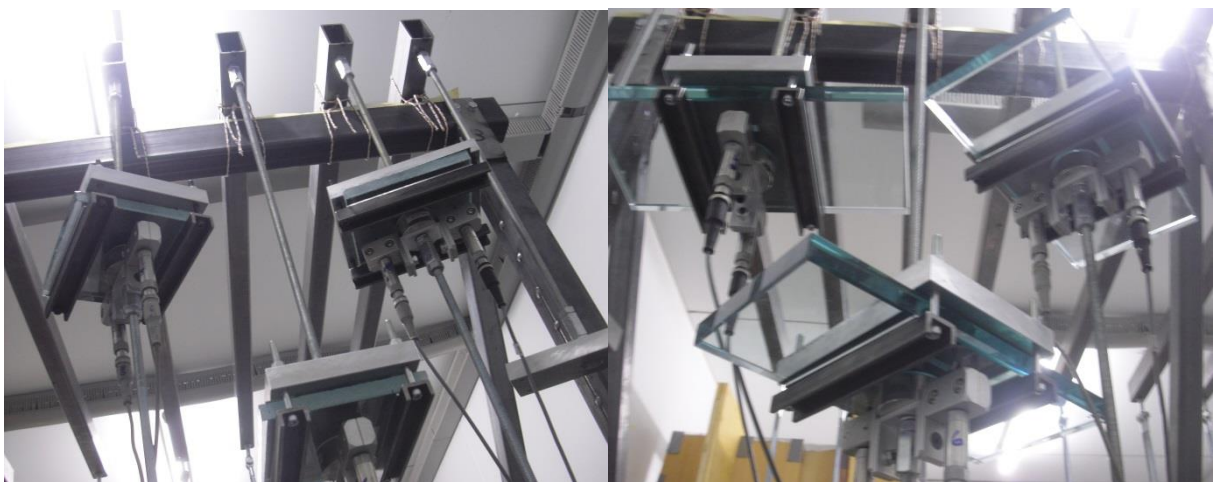


Figure 28 and 29 – Placement of the samples



Figure 22 – SGE specimens before assembly

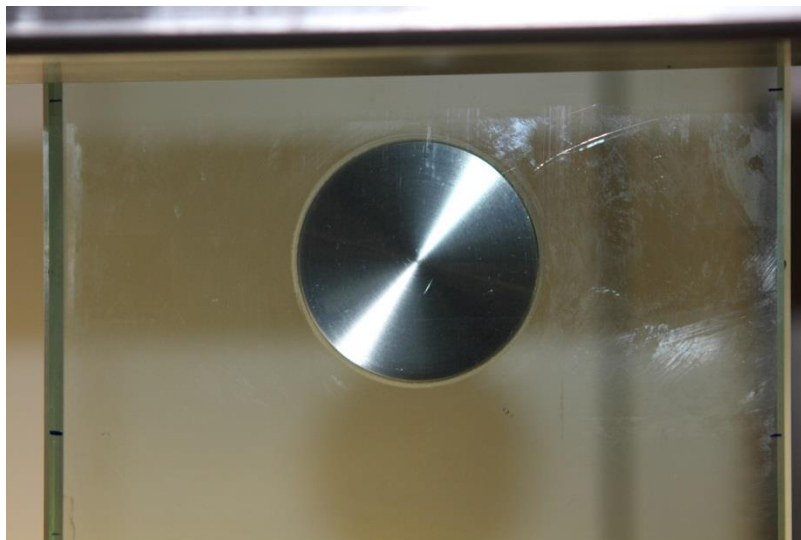


Figure 23 – Appearance of the adhesive without loading

### 8.3. Definition of pre-loading conditions

During the experiment, some samples were subjected to various, different effects as to analyze the influence of each and determine the condition of the LVDT's and the whole subject preparation in general.

These preparations will be described here and the graphs will be in annex as they are numerous and less relevant:

**-Subjects without loading at 20°:**

In order to see the variation of the temperature variation, the subjects were left in the climatic chamber with the normal variation of the chamber under 20°. [Table 1.1, 1.2, 1.3 of Annex]

**-Loading of subjects at 20°:**

All test samples were loaded at 20° for short term in order to analyze the elastic behavior of the adhesives. Some of the results will be used posteriorly in Table 53.

Some other LVDT's in the same samples had differential displacements like 0-2, 3-4 and 18-19. The reason was the fixing, which was a little looser in one side, leaving the specimen to rotate. This will always occur in these kinds of specimens which were minimized after. [Table 2.1, 2.2, 2.3 of Annex]

**-Unloading of specimens:**

The samples were then, unloaded. Some remained with residual displacements and others had simply some corrections to be made, possible only after discharged. [Table 3.1, 3.2, 3.3 of Annex]

**-Unloaded specimens:**

After being discharged, the LVDT's were corrected and it is shown the graphs of the subjects under temperature variation. [Table 4.1, 4.2, 4.3 of Annex]

**-Increase in temperature until 50°:**

The graphs show the increase in displacement due simply to the increase in temperature until 50. The behavior is as expected following the temperature curve. The LVDT's 3-4 continue to have differences in displacement and the 19 has irregular behavior. [Table 5.1, 5.2, 5.3 of Annex]

**-Loading and unloading of specimens under 50°:**

The specimens were again loaded and unloaded due to irregularities in 3-4, 18-19 and 17. [Table 6.1, 6.2, 6.3 of Annex]

**-Re-loading of all specimens:**

In this phase only 16-17 is reloaded to correct the LVDT's. [Table 7.1, 7.2, 7.3 of Annex]

### 8.4. Results

There is a lot of research in this area for creep measurement in adhesives at room temperature in which the creep can be predicted by simple expressions over time ([14]).

The specimens were all loaded, unloaded and reloaded in order to observe the viscoelastic properties of the adhesive. The displacement was considered 0 at the moment when the samples were considered stabilized after the temperature change at 50°.

It's important to note that in the displacement graph of SGE 3, the displacement fell to 0 in the second time simply because the range of the LVDT had been reached.

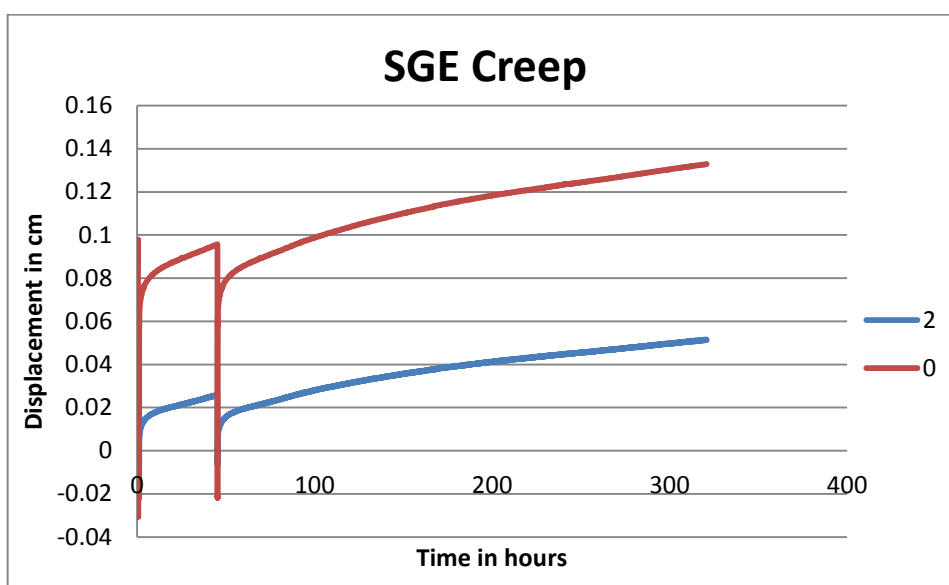


Table 44 – Displacements of SGE 1 under 50°.

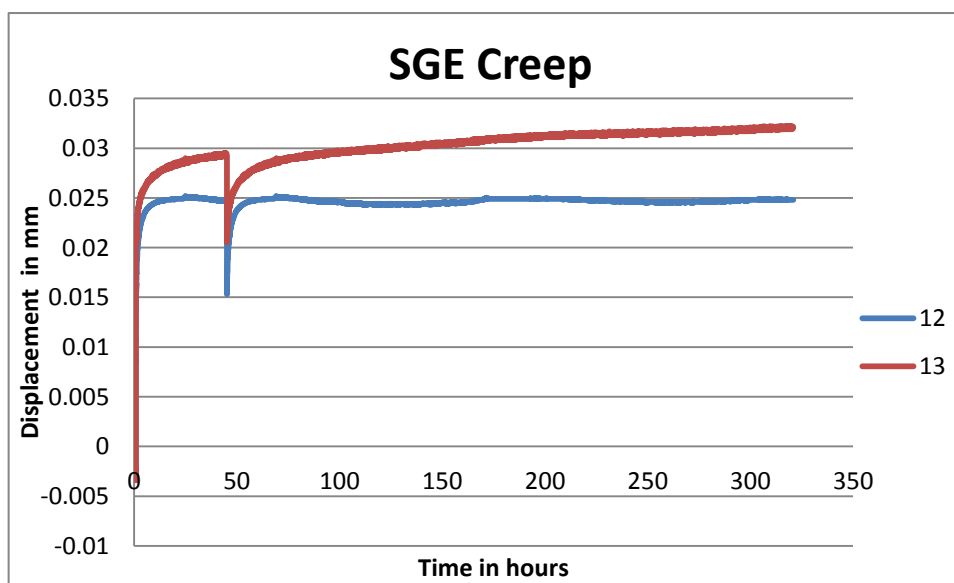


Table 45 – Displacements of SGE 2 under 50°.

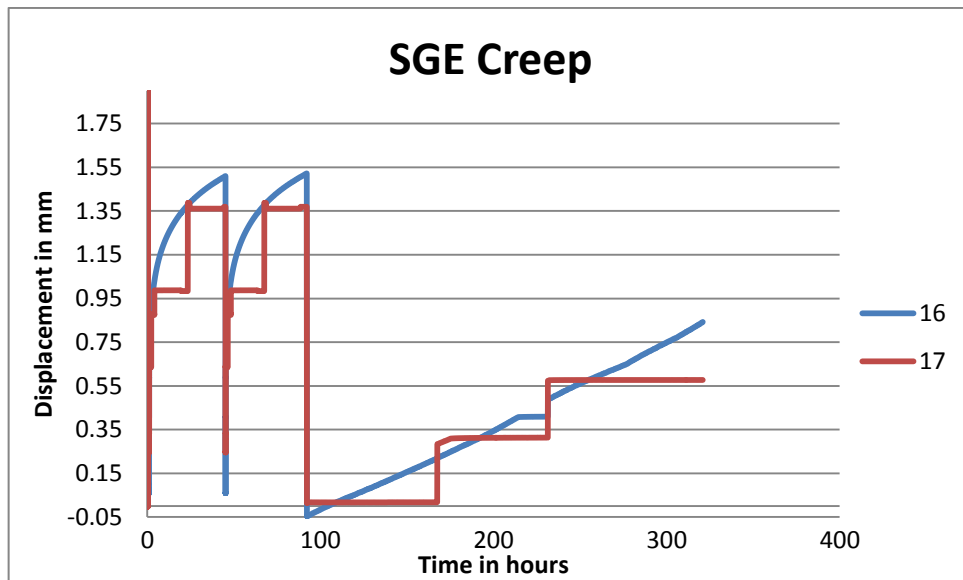


Table 46 – Displacements of SGE 3 under 50°.

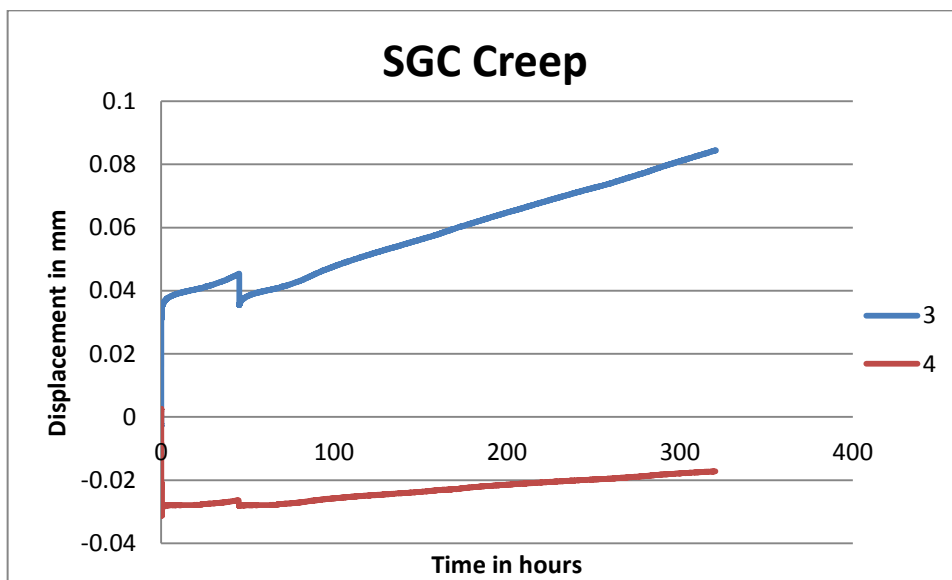


Table 47 – Displacements of SGC 1 under 50°.

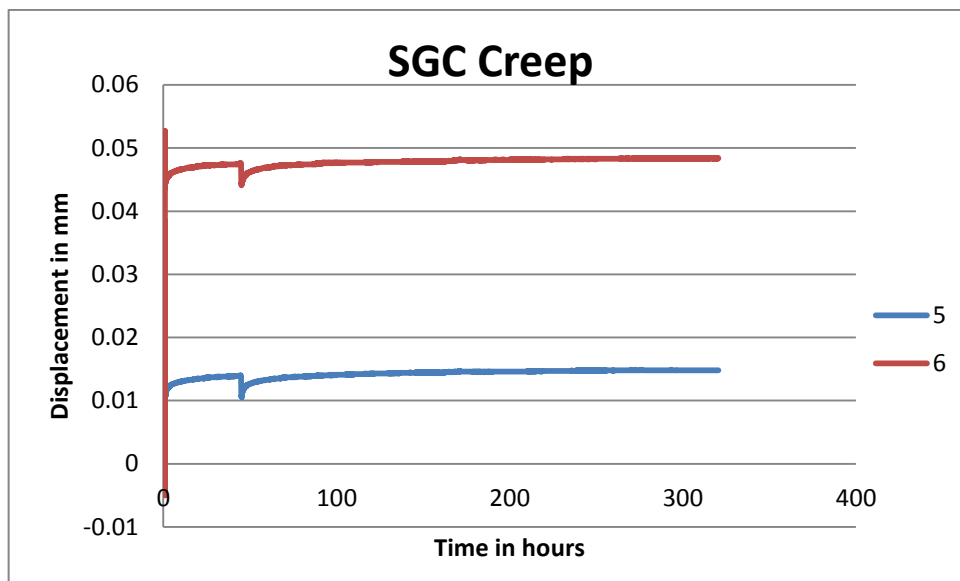


Table 48 – Displacements of SGC 2 under 50°.

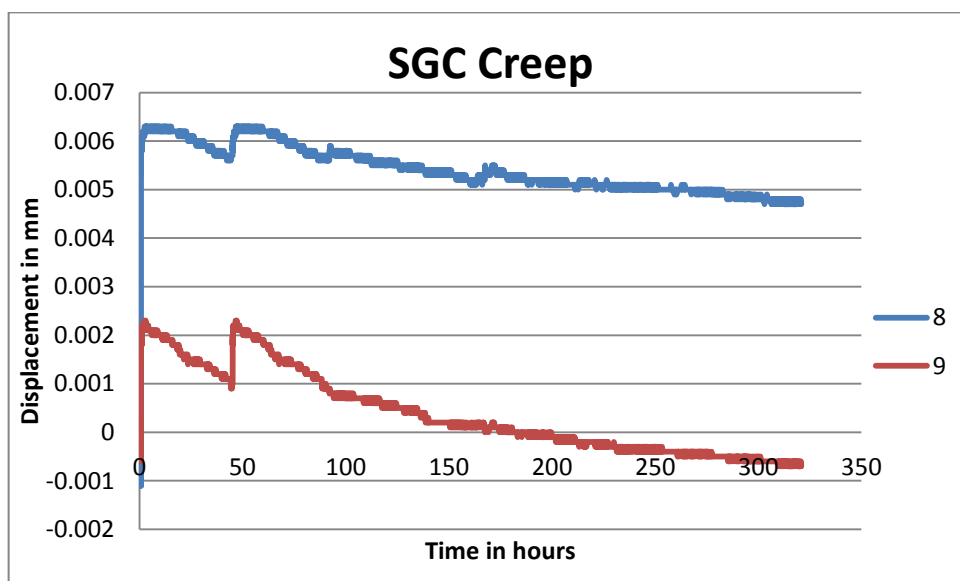


Table 49 – Displacements of SGC 3 under 50°.

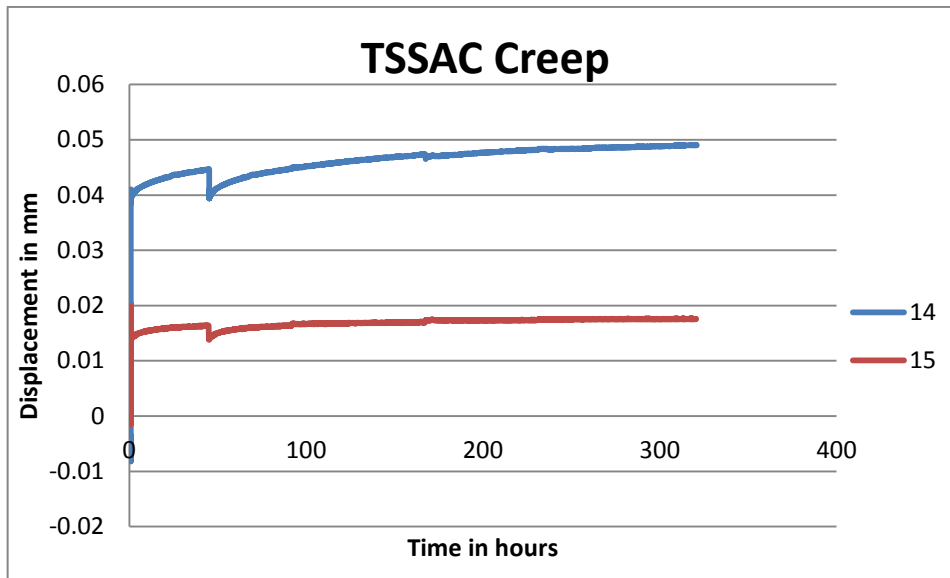


Table 50 – Displacements of TSSAC 1 under 50°.

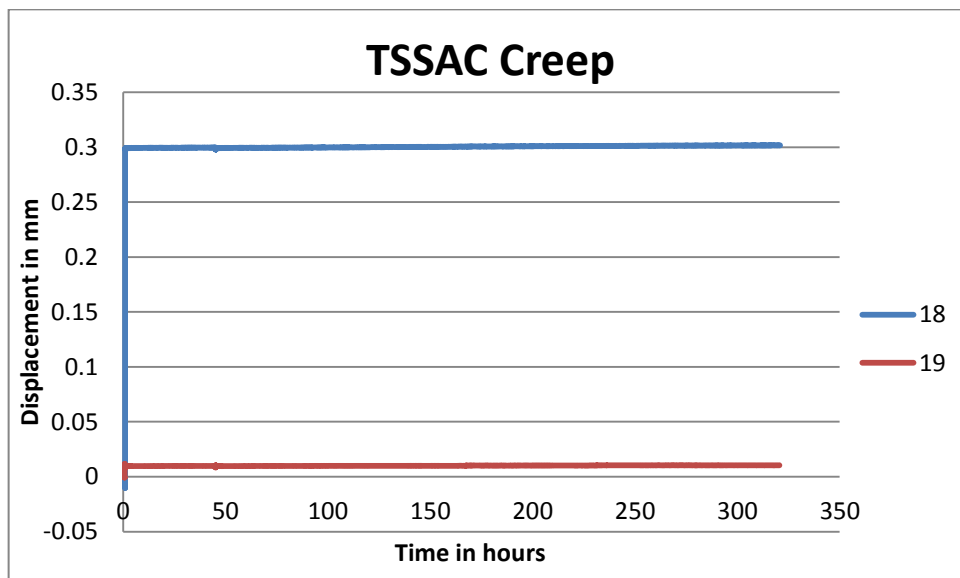


Table 51 – Displacements of TSSAC 2 under 50°.



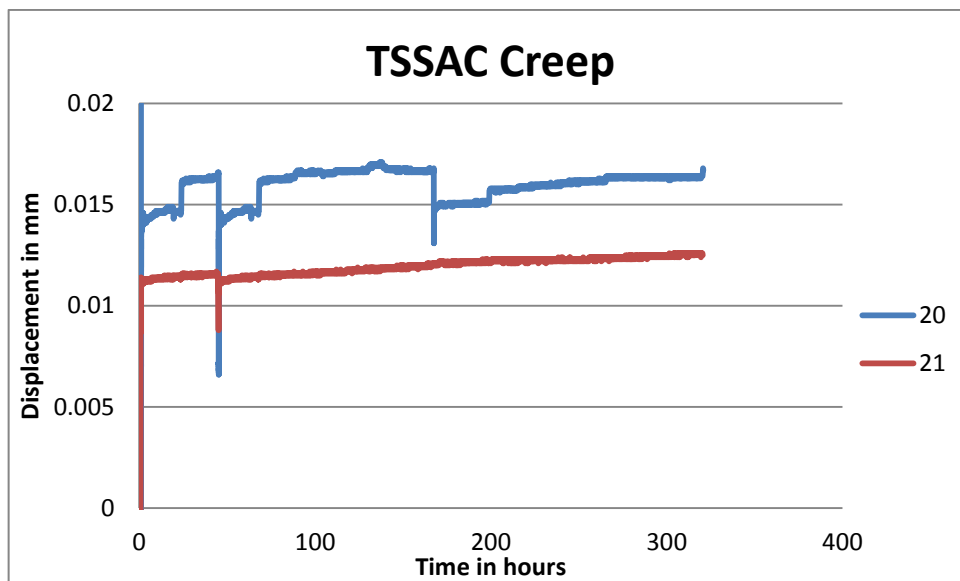


Table 52 – Displacements of TSSAC 3 under 50°.

In this analysis, even though the diagrams for each LVDT have the same shape through time, there is always a difference due to clearances in the supports. These clearances that can't be eliminated, only reduced, cause a slight rotation of the sample. In order to obtain the real displacement of the sample an average of the two is made.

### 8.5. Conclusions for the creep test

In order to summarize the behavior of the adhesive with the loading under 50° and 20° the following table was created. In this table we will determine the values of the average displacement of the adhesives with:

- Instant displacement of the specimen under 20° -measured 2000 seconds after the beginning of the graph (Annex-Table1.1, 1.2 and 1.3)
- Instant displacement of the specimen under 50° - measured 2hours after the beginning of the graphs (Tables from sub-chapter 9.1).
- Long term displacement of the specimen under 50° - final values of the graphs (Tables from sub-chapter 9.1).

Specimens	LVDT's numbers	Instant creep 20°	Instant creep 50°	Long term creep 50°
SGE1	0;2	0.00135	0.0435	0.09215
SGE 2	12;13	0	0.02335	0.02845
SGE 3	16;17	-	0.91725	0.70975
SGC 1	3;4	0.00314	0.0046	0.0336
SGC 2	5;6	0.0001	0.02885	0.0316
SGC 3	8;9	-	0.0042	0.002
TSSAC 1	14;15	0.00005	0.02755	0.0333
TSSAC 2	18;19	0	0.15445	0.156
TSSAC 3	20;21	0	0.01285	0.0146

Table 53 – Displacements of all samples.

It's interesting to verify that the adhesives have a complete viscoelastic behavior even under 50° recovering the un-deformed original position over time. In most of the cases, the specimens were only unloaded during some minutes, not allowing the adhesive to recover the un-deformed position but seem to show exactly the same behavior after re-loading.

It's possible to see from the previous table that the instant displacement is higher with the samples under 50°, like predicted, and the significant difference of displacement. In some cases, the samples deform substantially in long-term and, in others, maintain the short term displacement.

Depending on the loading in each case, the displacement can seem to stabilize at a certain value or to continue to deform linearly with no limit in the cases of SGC1, SGE1 and SGE3. This linear behavior of deformation can be very useful to investigate since it will lead to failure. It's important to know, for adhesive connections, the limit of tension admissible in each sample typology for prevention of failure in a long term.

This maximum tension wasn't reached in TSSAC. In SGC this tension was reached on SGC 1, meaning that the maximum tension for this case has a value between 7,01 KN and 7,89 KN. For SGE this value was reached for both SGE1 and SGE3 meaning that the maximum tension is located between 3,52 KN and 1,59 KN assuming that the displacement in SGE2 will stabilize. The TSSAC samples would have to be loaded with more charge in order to determine the interval in which this failure process would occur.

In these kind of connections it's very interesting to study the whitening of the adhesive, a phenomenon that occurs next to the limit tension at a certain displacement that can be used to predict failure. This phenomenon occurs with creation of air bubbles and white coloration on the adhesive. There is no information until the time of this thesis when and if this will occur in the specimens.

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