Behaviour of structural glass at high temperatures

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MSc Civil Engineering

“He who loves practice without theory is like the sailor who boards ship without a rudder and compass and never knows where he may cast.”

Leonardo Da Vinci

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By

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Preface

The current research, titled “Behaviour of Structural Glass at High Temperatures” finalizes my Master program Building Engineering at the faculty of Civil Engineering and Geosciences at Delft University of Technology, specialized in Structural Design. This study has been executed partially at ABT and partially at Efectis, in the period from October 2015 to Augusts 2016.

Many people and organizations contributed their time, effort and ideas to the realization of this thesis. To begin with, I would like to express my gratitude to the graduating committee for their guidance, advice and suggestions during my research.

In particular, I wish to express my sincerest gratitude to Diana de Krom from ABT. This work could not have been accomplished without her contribution, guidance and help.

I would like to thank Gert van den Berg and Arnoud Breunese from Efectis. Without their guidance and assistance the outcome of this research would not be the same.

Furthermore, my gratitude goes to Rob Nijsse for chairing my graduation committee, his valuable advice and the productive discussion during my research.

Moreover, my special gratitude to Fred Veer, who has supported me throughout the whole process with his valuable knowledge, his help and his patience.

I want to thank also Christian Louter, for his opinions, his guidance and the valuable information regarding glass testing at Empa.

I wish to thank Roel Schipper whose knowledge in glass and useful advice encouraged me to start and complete this topic.

I would sincerely like to thank the engineering company ABT and Efectis for offering me the opportunity to work on this project. They gave a lot of support and help. Special thanks to Robert Scheepe and Saskia Nieuwendijk for their valuable help and for assisting me in the experiments. Without them I would not have been able to perform my tests in the lab. Moreover, I would like to thank Stefan de Kool from ABT for his information and his valuable time he spent during my literature study.

I would like to thank AGC Glass Europe for their sponsoring and interest in my research.

Finally I want to thank my family for their endless support given me all this years of my student life.

Abstract

Key words:

Fire behaviour, testing, structural glass, annealed, fully tempered, heat strengthened

This thesis presents a study on the behavior of none-structural and structural glass at high temperatures. The main objective of this master thesis is to investigate the capabilities of different glass types when these are used as a structural element with fire resistant requirements. It is therefore important to develop an understanding of the behaviour of various glass types subjected to fire.

A literature study is done on glass properties, glass production and methods for making structural glass. The purpose of this study was to investigate the background information and to gain adequate knowledge about the state of art on the thesis topic. Moreover thermal and mechanical properties of glass were determined. Results of these studies show that all glass properties depend on temperature. Subsequently the finite element model (first DIANA model) was made to simulate a glass test which was performed by others at Empa in Switzerland. A laminated beam model was made in DIANA software. This beam consists of 3 soda lime glass layers and two sentry glass interlayers. This model was used for making a sensitivity analysis about the glass properties which were found during the literature studies. The sensitivity analysis showed that from the material properties uses as input for DIANA models, the heat specific property has the most influence on the glass temperature.

As next step, six experiments series were performed at the laboratory of Efectis Netherlands BV in Bleiswijk. The purpose of these tests was to investigate fire behaviour of three different glass types. Annealed, fully tempered and heat strengthened glass were tested horizontally and vertically in different conditions during these experiments. Results of each test were analyzed and discussed before performing the next test. This way, the knowledge about the fire behaviour of the glass and the right method for test performing was developed step by step during this research. Annealed glass performance was very weak at high temperatures due the thermal break phenomenon. It seems to imply that annealed glass (without any improvement) does not have the capabilities to be used as a fire resistant structural element. Based on the different behavior of steel and glass at the high temperature, can be noted that the thermal break phenomenon is occurred at the joint locations (connection between glass and steel support). For this reason joint details need extra attentions if glass needs to be used as a fire resistant structural element. The tests observations shows that 550-600°C is the critical temperature for both fully tempered and heat strengthened glass types. The average furnace temperature was around 615°C when glass temperature reached the critical temperature (550°C). The glass behavior changed to plastic phase at the critical temperature. Therefore the glass was not solid anymore and behaved more like liquid material. Afterwards the glass was not able to carry any loads, even not the self-weight. Through the data analysis and the observations of test series 1 to 6 seems to imply that fully tempered and heat strengthened glass, with some improvements, have the capabilities to be used as a structural material under fire loads. It should be mentioned that the relation between maximum allowable tensile stress and temperature, need to be determined first. This information is essential in order to determine if fully tempered glass can be used as fire resistant element. Test setups and the results of the tests are discussed in the chapter “Tests at Efectis” in more details.

Single glass layer is tested during all the experiments series. The results show that one layer was not sufficient. This means that using laminated glass is essential in order to have enough fire resistance. The interlayers and the outside glass layers can keep the temperature of the middle layer(s) (loadbearing part) below the critical temperature for certain amount of time.

Second DIANA model was made for one of Efectis test in order to see if the finite element model could give a correct estimation of glass behavior at high temperatures. The model results were close to the ones found during the tests. This means DIANA model has the capabilities to predict glass behavior at high temperature. In order to be able to make a model with more precision, glass properties need to be determined. For this reason several material tests should be performed at the beginning of the next research.

Metal wires are used for the deflection measuring. The results show that these wires are extended considerably during the performed tests. For this reason this method is not useful for a correct deflection measuring. A new measuring method should be determined in order to have no physical connection between measurement equipment and glass. This way makes measuring glass deflection directly (without any instrument like metal wire) possible.

Thermocouples were used for measuring glass temperature surface. These thermocouples were installed on the glass surface. Thermocouples can be placed between layers of laminated glass during the glass production. This way makes more precision temperature measuring possible.

Contents

1 Introduction

This chapter describes some motivations and reasons for choosing the fire behavior of structural glass elements as the topic for the master thesis. Moreover the main objective and the research questions of this thesis have been mentioned here. In addition, this chapter describes the strategy and the planning for different stages during this thesis.

Nowadays the use of glass is wildly increased. For instance, famous technology-companies like Apple use structural glass in their stores. These companies use this technology in order to illustrate the innovative philosophy of their brand.

Figure 1.1 Apple store in NY city (Source:www.greatnewsmag.com)

Moreover, using glass offers many advantages to the users as well. Transparency is an important property of the glass. This gives glass a unique position when compared to other building materials. Furthermore, glass is completely watertight and it does not need any kind of protection such as paint. Glass is also 100% recyclable which means it can be recycled endlessly. Glass recycling can be done with no loss terms of its quality or purity.

In recent decades, researchers have been working on using the material glass for structural elements. Even though it might sound surprising to most people, it is possible. For instance, Pavilion by the Glasbau Hahn (1950) is the first construction using this modern development. Several large span (>12 m) glass beams have been constructed since. Examples for the application of structural glass are shown in the next pages.

Figure 1.2 Exposition pavilion by Glasbau Hahn firm, 1950's. (Source:www.detail-online.com)

Figure 1.3 14 m span courtyard roof covering IHK Munich Engineering (F. P. Bos)

Figure 1.4 Glass suspension bridge spans between two cliffs in china's shiniuzhai park (Source: www.designboom.com)

Figure 1.5 Glass suspension bridge in china's shiniuzhai park (Source: www.designboom.com)

Although there are various limitations to using glass as a structural element, the low fire resistance of glass can be mentioned as a crucial issue in this field. Therefore there is a need to develop proper precautions against the effect of fire in the building design industry. Researchers and engineers have developed different kinds of improvements in this field. There are possibilities such as borosilicate glass and the intumescent coating which can improve fire safety of structural glass elements. Before taking such measures, a better understanding of the behavior of glass during fire is needed. This research, therefore, focuses on the study the behaviour of non-structural and structural glass at high temperatures.

2 Methodology

2.1 Objective

The main research objective of this thesis is study the behaviour of various glass types at high temperature, with 'high', the temperature range is meant that can be expected during fire in buildings. This study is essential in order to determine the capabilities of glass when it should be used as a structural element under high temperature load (as fire resistant structural element).

2.2 Research Methodology & Research Questions

The following structure is used for carrying out this research:

Orientation & preparation work

The relevant information is gathered in order to describe the major research questions. The research questions which should be answered are:

- *How does annealed glass behave during fire?*
- *How does fully tempered glass behave during fire?*
- *How does heat strengthened glass behave during fire?*

Literature study & making first DIANA model

A literature study is done on glass properties, glass production and methods for making structural glass. The purpose of this study was to investigate and critically analyze the background information about the subject of the thesis.

Dr. Christian Louter has tested the performance of several structural glass elements at Empa in Switzerland, which were among the first experiments in this field in the world. An important part of the present thesis was to model one of these elements in DIANA software. The results of this modeling is compared to available test results. This model is also used for making a sensitivity analysis about the glass properties which has been found during the literature studies. This step helped to answer the following research questions:

- *Is it possible to model the glass elements exactly the same as those tested at Empa?*
- *Do the results of the tests and the models match?*
- *Which property has the most influence on the glass temperature and the deflection?*

Preparation for Efectis tests

The performing of tests needed extra attention for the communications and the management skills. An important task was the looking for a company that sponsor the glass specimen. AGC Glass Europe accepted to be the sponsor for this research. Moreover various test setup drawings were made in this stage. These drawings were used to communicate with colleagues in the lab. This step helped to find a sufficient answer for the following question:

- *How should the glass be tested at Efectis? What are the requirements?*

Testing at Efectis

Six experiments were performed at the laboratory of the Efectis. The purpose of these tests was to investigate fire behavior of three different glass types. Annealed, fully tempered and heat strengthened glass were tested horizontally and vertically in different conditions during this research. Test setups of these tests are discussed in the chapter "Tests at Efectis" in more details.

Analyzing results

Results of each test were analyzed and discussed before performing the next test. The knowledge about the fire behaviour of the glass and the right method for test performing was developed step by step during this research. Test setups and the results of these tests are discussed in the chapter "Tests at Efectis" in more details. Another DIANA model was made for one of the Efectis tests. The model results were compared to results derived from testing. The results of this comparison were analyzed in order to provide answers to the research questions. The possible modifications and new tests were done in this stage. The following questions were also relevant for this stage:

- *Is it possible to model the glass elements exactly the same as those tested at Efectis?*
- *Do the results of the tests and the models match?*

Finalization

Final results analyses are made in this part of my research. Final report is completed in order to get a green light for the final graduation meeting.

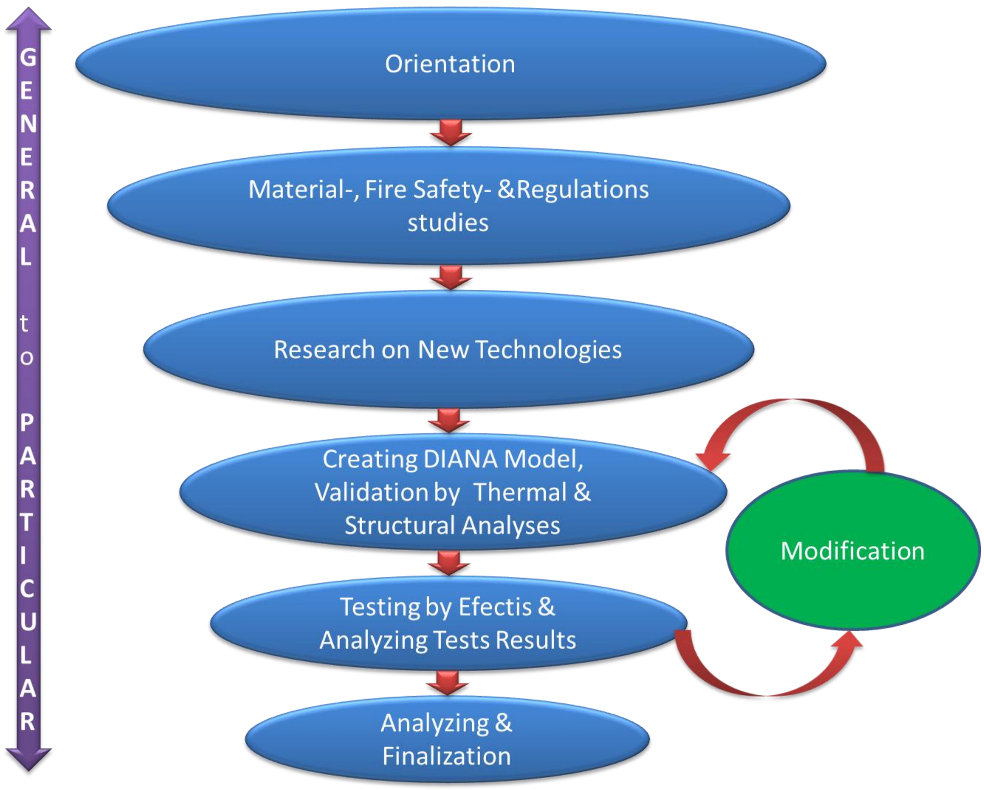


Figure 2.1 Plan of Work

3 Literature Study

3.1 Glass as a Material

It is essential to have sufficient knowledge about glass as a material and its properties. To achieve this end, the current glass material products and its properties will be shortly reviewed in this section. In addition, this section offers a clear overview about the pros and cons of this product and its properties.

3.1.1 Compositions and Chemical Properties

Glasses are fused products of inorganic oxides. They are cooled down to a rigid condition. This process happens without forming a crystal. The difference between glass and crystal is about their molecules arrangement. Silicon dioxide is a fundamental composition of every glass type. "In a crystal, molecules are arranged in a repetitive, periodic pattern. In glass, by comparison, they are arranged in a disorderly fashion: glass is amorphous. Correspondingly, in glass the molecules are not densely packed."(Fedor Mitschke, 2009)

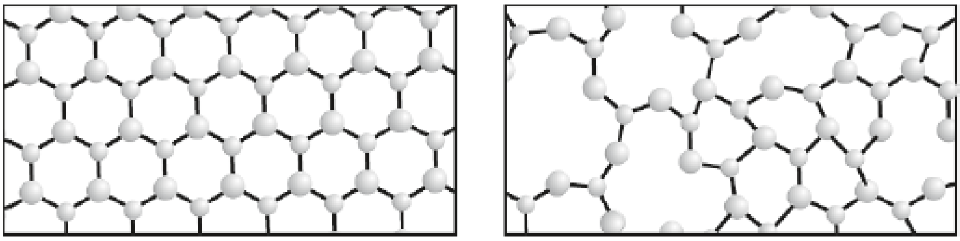


Figure 3.1 Examples of crystal and glass structure

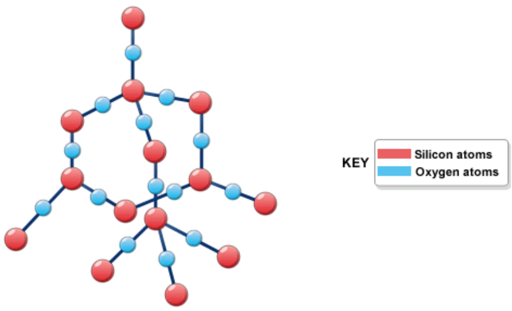


Figure 3.2 Molecule of SiO_2 (Source:www.bbc.co.uk)

Figure 3.3 Quartz is pure crystalline silicon dioxide (Source:https://johnvagabondscience.wordpress.com)

Vitreous silica is a type of glass which is produced form pure Silicon dioxide. Other glass types need more chemical compositions such as Na_2O, CaO, B_2O_5 etc. However, SiO_2 is the compound which mainly gives the structure to the material. Common silicon dioxide glasses are briefly reviewed in the following paragraphs.

Vitreous Silica Glass

Fused quartz and fused silica glass are two other names for this glass type. As mentioned before, this material is built up from SiO_2 alone.

"Fused quartz is manufactured by melting naturally occurring crystalline silica, such as sand or rock crystal. The production method is either electrically fused or flame fused. Afterward, items will appear transparent, translucent, or opaque; making it possible to create a wide range of products. Fused silica, commonly referred to as synthetic fused quartz, is produced using high purity silica sand that is manufactured from $SiCl_4$. The finished product's appearance will be transparent. Vitreous Silica, in all its forms, offers a variety of properties such as:

- Permeability
- Extreme Hardness
- Very Low Coefficient of Thermal Expansion
- Resistance to High Temperature (1000-1500 °C)
- High Chemical Purity
- High Corrosion Resistance
- Extensive Optical Transmission from Ultra-Violet to Infra-Red
- Excellent Electrical Insulation Qualities
- Remarkable Stability Under Atomic Bombardment" (www.technicalglass.com)

Furnace tubes, lighting tubes and melting crucibles are examples of its application.

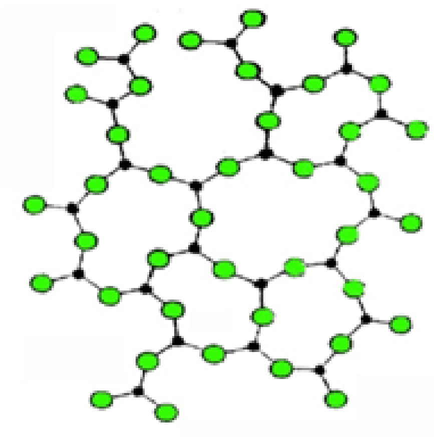


Figure 3.4 Example of vitreous silica structure rollers for glass (Source: http://community.ceramicartsdaily.org/)

Figure 3.5 Kiln Supporting furnace Vitreous Silica ceramic tempering furnace (Source: http://www.alibaba.com)

Soda Lime Silica Glass

The Soda lime silica, the borosilicate and the lead silicate glasses are three types which are produced mainly in industry. The soda-lime-silica is the glass type which is used for the production of float glasses. The soda-lime-silica glasses are product mainly of silica (SiO_2), sodium oxide (Na_2O) and calcium oxide(CaO). Its heat resistance is low (500-600 °C). Moreover, it has high thermal expansion.

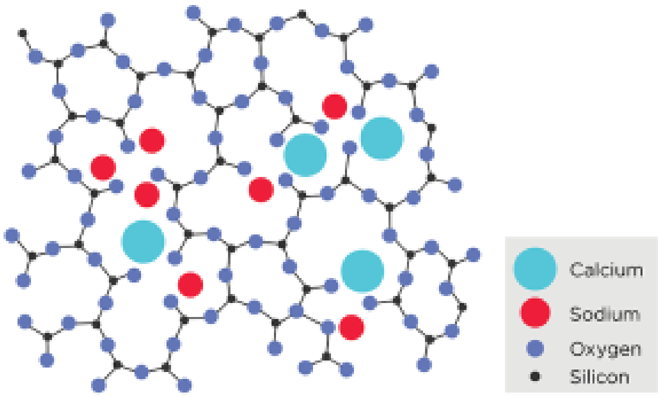


Figure 3.6 Example of Soda lime silica structure (Source: www.koppglass.com)

Chemical	Symbol	Percentage
Silicon dioxide (silicate)	SiO_2	69-74%
Calcium oxide (lime)	CaO	5-12%
Sodium oxide (soda)	Na_2O	12-16%
Magnesium oxide	MgO	0-16%
Aluminium oxide	Al_2O_3	0-5%

Table. 3.1 Chemical composition of Soda lime silica structure (Source: www.metroglasstech.co.nz)

This is a transparent material and can be easily formed. For instance this type of glass is used for most the windows-glazing of the buildings. Bottles, “low temperature incandescent light bulbs” and tableware are some examples of its applications. In addition, “container glass is a soda lime glass that is a slight variation on flat glass, which uses more alumina and calcium, and less sodium and magnesium which are more water-soluble. This makes it less susceptible to water erosion”(https://en.wikipedia.org/wiki/Glass).

Sodium Borosilicate Glass, Pyrex

This type of glass has much lower heat expansion than the previous one. Silicon dioxide, boric oxide and smaller amounts of the alkali aluminum oxide are three chemical compositions which make the structure of the borosilicate glass. “They have fairly low coefficients of thermal expansion (7740 Pyrex CTE is 3.25×10^{-6}/°C) as compared to about 9×10^{-6}/°C for a typical soda lime glass, making them more dimensionally stable. The lower coefficient of thermal expansion (CTE) also makes them less subject to stress caused by thermal expansion, thus less vulnerable to cracking from thermal shock. They are commonly used for reagent bottles, optical components and household cookware.” (http://www.quartz.com/ and http://www.us.schott.com/)

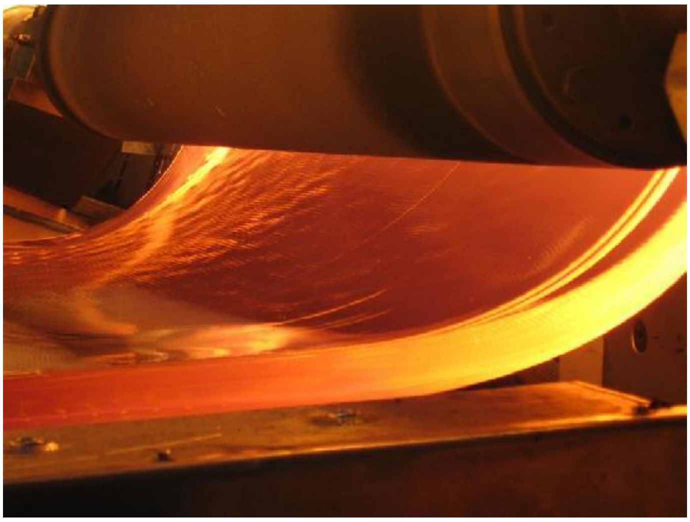
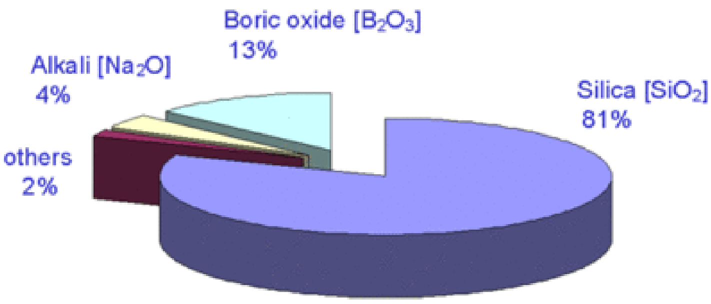


Figure 3.7 Rolled borosilicate glass sheets (Source: http://www.us.schott.com/)



Graph. 3.1 Chemical composition of Borosilicate glass (Source: http://www.qvf.com/)

Lead Oxide Glass, Crystal glass

Lead oxide glass is composed of silica (59%), lead oxide (25%), potassium oxide (12%), smaller amounts of soda, zinc oxide and alumina. This glass has high density; this property gives a crystal look to this glass; however, glass does not have crystal structure. Moreover, it has good elasticity. But it is not resistant to heating.

Aluminosilicate Glass

“A small, but important type of glass, aluminosilicate, contains 20% aluminium oxide (alumina-Al_2O_3) often including calcium oxide, magnesium oxide and boric oxide in relatively small amounts, but with only very small amounts of soda or potash. It is able to withstand high temperatures and thermal shock and is typically used in combustion tubes, gauge glasses for high-pressure steam boilers, and in halogen-tungsten lamps capable of operating at temperature as high as 750°C." (http://www.britglass.org.uk/)

Figure 3.8 Gorilla Glass features an alkali-aluminosilicate (Source: http: //www. glassmagazine.com/)

Composition	(wt%)
SiO_2	50-75
AL_2O_3	7-25
B_2O_3	0-20
Li_2O - Na_2O + K_2O	0-4
MgO + CaO + SrO + BaO + ZnO	5-25
TiO_2 - ZrO_2	0-10
P_2O_5	0-5

Table. 3.2 Chemical composition of Borosilicate glass (Source: http://www.google.com/patents/)

Oxide glass

This glass is very clear; moreover, it is composed mainly of alumina (90%) and smaller amount of germanium oxide (GeO_2)." Oxide glasses with large non-linear refractive index and non-linear absorption coefficient are promising materials for fiber telecommunication and for non-linear optical devices such as ultrafast optical switches, power limiters, real time holography, self-focusing, white-light continuum generation and photonic applications"(M. Abdelbak, F. Eldiasty 2006).

3.1.2 Material Properties

Transparency

"In the field of optics, transparency (also called pellucidity or diaphaneity) is the physical property of allowing light to pass through the material without being scattered"(Wikipedia, transparency). There is nothing for light absorption in visual frequencies. For this reason photons are not absorbed and these pass through glass. "Any photon has certain frequency which for visible light is related to the colour of light, whilst for lower or upper frequencies in the electromagnetic spectrum it is simply a measure of the energy transported by photon. A material's absorption spectrum depends on the structure of the material at atomic scale. Absorption may be from atoms which absorb photons, from molecules, or from lattices. There are important differences in these absorption possibilities:

- Atoms absorb well defined discrete frequencies. Usually single atoms absorb only a few frequencies. This depends on the energetic spectrum of its electrons. Regarding atomic absorption, the graph of absorption (plotted as a function of frequency of light) contains well-defined peaks for frequencies when absorption occurs, and no absorption at all between them.
- Molecules absorb discrete frequencies but there are many more absorption lines because even a simple molecule has many more energetic levels than any atom. So molecules absorb much more light.
- Crystalline lattices may absorb not only discrete frequencies but also continuous bands of frequencies, mainly because of discrepancies in the crystalline structure

As glass is a non-crystalline, overcooled fluid, consisting of molecules, its absorption occurs in the 1st and 2nd ways, but because of the matter it is composed of, it absorbs outside our visible spectrum" (http://physics.stackexchange.com/)

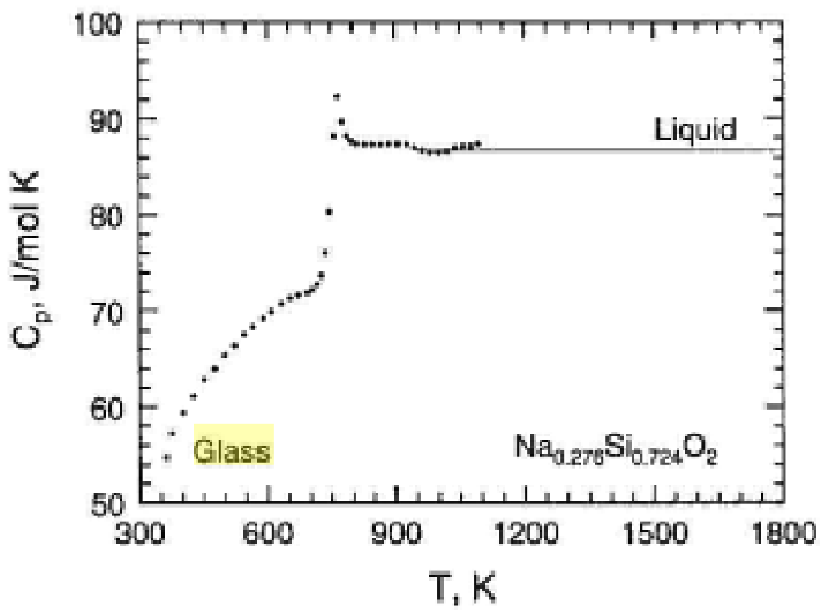
Figure 3.9 Transparency (Source: www.trendhunter.com)

Thermal Properties

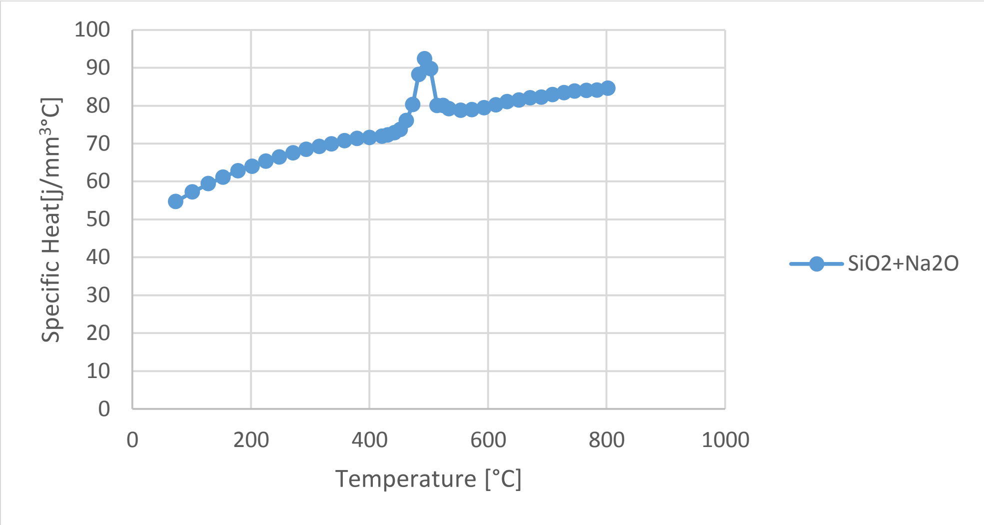
The specific heat capacity, thermal conductivity and expansivity are three important thermal properties for glasses. They are related to the atoms vibration. "As the temperature is raised the amplitude of vibration and thus the energy associated with each vibration atom increases. For most solids near room temperature this is the only mechanism leading to a significant change content with temperature so that the heat capacity (specific heat capacity x mass) of theses solids is simply the rate of the total vibrational energy with temperature. When a temperature gradient exists in a solid the amplitude of the atomic vibrations will be grater in the hotter region. In non-metallic solids, the conduction of heat is entirely due to the transmission of theses vibrations, i.e. to the propagation of mechanical waves through the solids. ” (D. G. Holloway, 1973)

Specific Heat Capacity

The heat specific value of an object shows the actual amount of heat needed for temperature change in that particular object. The specific heat capacity changing for the two types of glass has been illustrated in the following graphs. First one shows the specific heat values for $NaSiO_2$ glass and the next one presents the values for the compositions of Na_2O and SiO_2. This is almost similar to the compositions of the soda-lime-silica. Unfortunately, the exact data for soda-lime-silica glass are not available at high temperatures. Therefore the data of the compositions of Na_2O and SiO_2 were used in the models.



Graph. 3.2 Specific Heat Specific change for $NaSiO_2$ (Source: Silicate Glasses and Melts by P.Richet & B. O.Mysen)



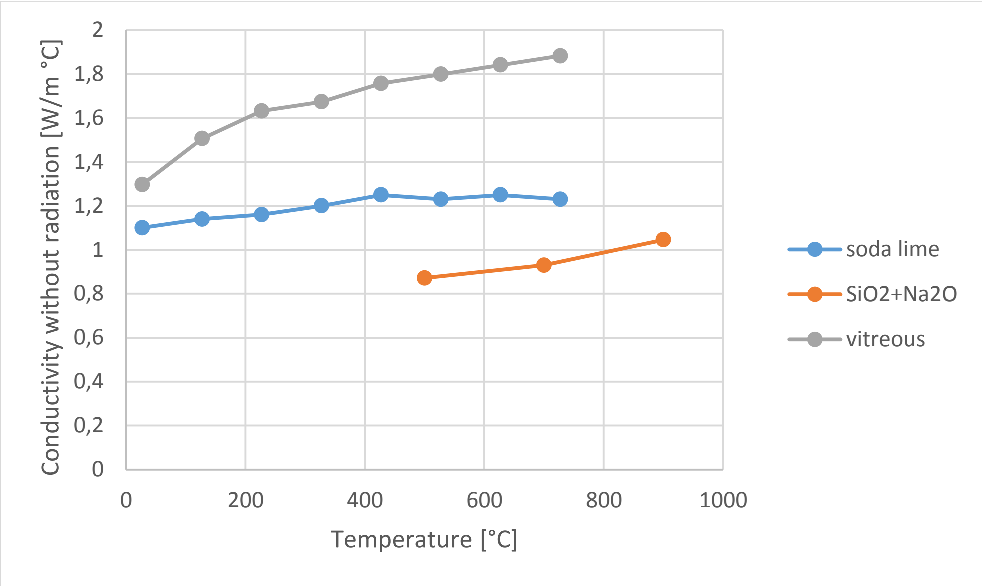
Graph. 3.3 Specific Heat Specific change for SiO_2 & $27.6Na_2O+72.4SiO_2$ (Source: Handbook of Glass Data, Mazurin, Streltsina and Shavaikovskaya, 1983)

Thermal Conductivity

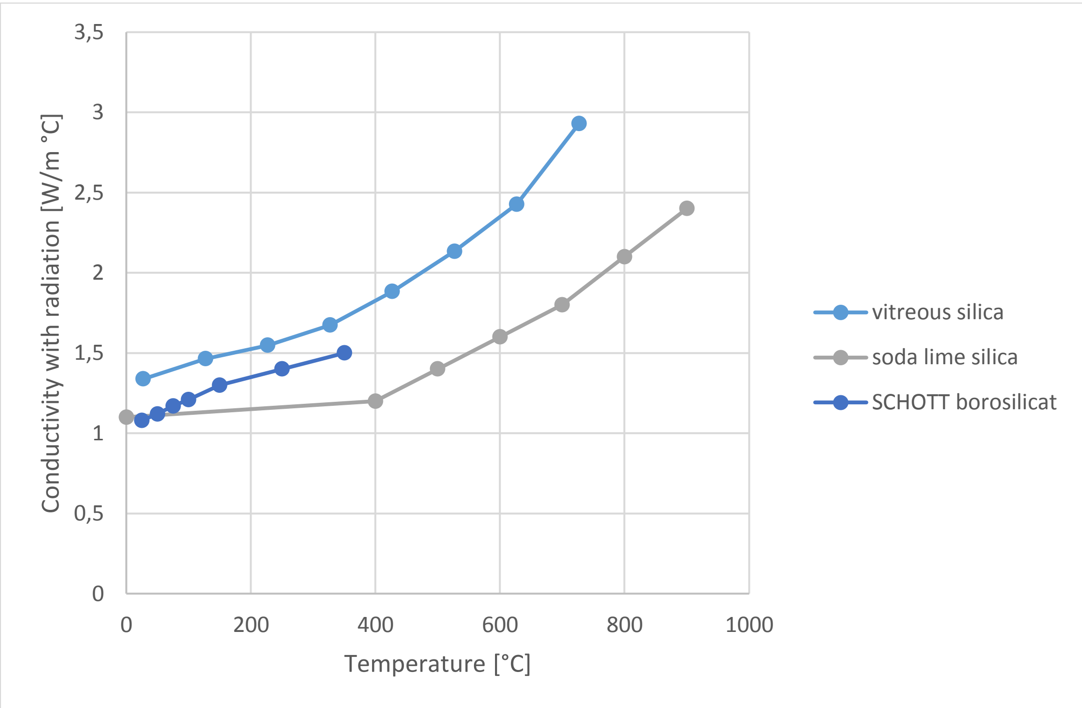
This property shows the ability of glass to conduct heat. Thermal conductivity can be defined as:

"The quantity of heat transmitted through a unit thickness of a material - in a direction normal to a surface of unit area - due to a unit temperature gradient under steady state conditions"

Various data about conductivity obtained from the literature has been illustrated in the followings graphs. Vitreous silica and borosilicate have a sharp rise at high temperatures. The growth for the composition SiO_2 and Na_2O is slightly. The gray's graphs shows a dramatically surge for window glass (soda lime), which has been founded in the lecture's slides of Prof. Lehman. He did many researches in the field of glass and ceramic properties. But he does not mentioned the references for this values. The yellow graph shows a very small variation. The values have almost a period of stability. This graph is obtained from book Conductivity 22.



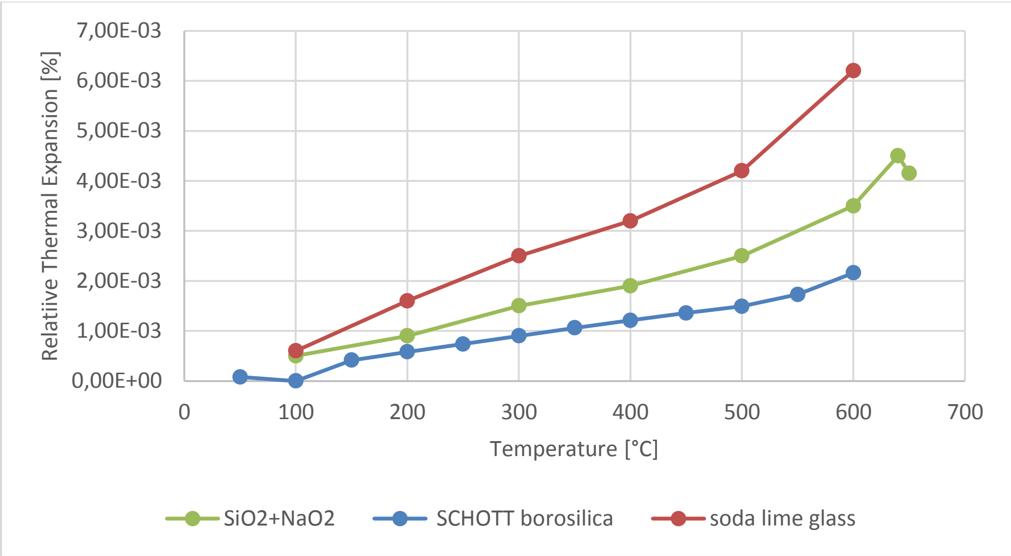
Graph. 3.4 Thermal conductivity dependence of temperature. Data on soda lime glass was obtained by Timothy W. Tong (book conductivity 22). Those on SiO2+Na2O were obtained by o. v. mazurin, m. v. streltsina and shvaikovskaya (book physical sciences data 15 handbook of glass data).



Graph. 3.5 Thermal conductivity dependence of temperature. Data on window glass (soda lime glass) was obtained by Prof Richard Lehman. Those on vitreous glass were obtained by o. v. mazurin, m. v. streltsina and shvaikovskaya (book physical sciences data 15 handbook of glass data).

Thermal Expansion

The Graph. 3.6 Thermal expansion dependence of temperature. Data on SiO2+Na2O was obtained by o. v. mazurin, m. v. streltsina and shvaikovskaya (book physical sciences data 15 handbook of glass data). shows that borosilicate has lower heat expansion than soda lime glass.

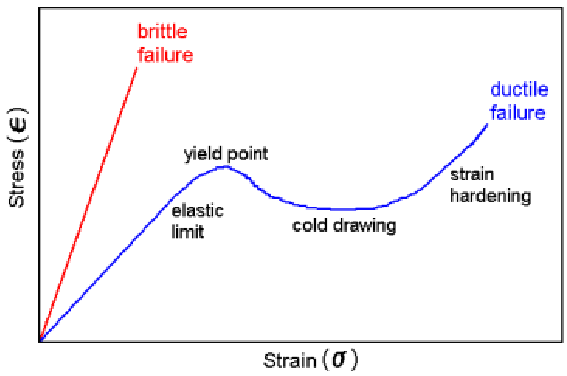


Graph. 3.6 Thermal expansion dependence of temperature. Data on SiO2+Na2O was obtained by o. v. mazurin, m. v. streltsina and shvaikovskaya (book physical sciences data 15 handbook of glass data).

Mechanical Properties

Strength

Glass is known as a brittle material which has no plastic behavior. For this reason glass break without any warning. “The strength of glass depends on a variety of factors. Most of them are related to the breaking behaviour of glass or in other words the lack of plasticity. Although glass seems like a perfect homogeneous material it is never perfect. On the surface of the glass and especially on the edges micro cracks are present due to glass’s fabrication process (sawing, cutting, drilling, edge and surface grinding). Whenever a glass pane is loaded by wind for instance, stress can get locally higher than the covalent bond between the atoms around those micro cracks and the crack will start to widen. The atoms around the micro crack lack the capability to regroup or replace themselves because they cannot deform plastically. This results in an even higher stress level and an unstoppable cracking behavior”(F.A.Veer, 2007)



Graph. 3.7 Graph comparing stress–strain values for glass and steel (source: www.anasys.co.uk/library)

Young's modulus

For modeling and designing a structure from the glass material, it is also essential to have sufficient knowledge about the mechanical properties such as E modulus. Dr. Rouxel shows E values for different materials at high temperatures. The data for soda lime were obtained by means of ultrasonic echography. The graph begins at the point of 7 °C with a value of 72 GPa for E modulus. The E value at 727 °C is the last point which he has measured. The soda lime has around 53 GPa at this point, which is more than my predication at such high temperature. This graph shows that soda lime declines steadily from the beginning to 527 °C. Afterwards its drops more rapidly.

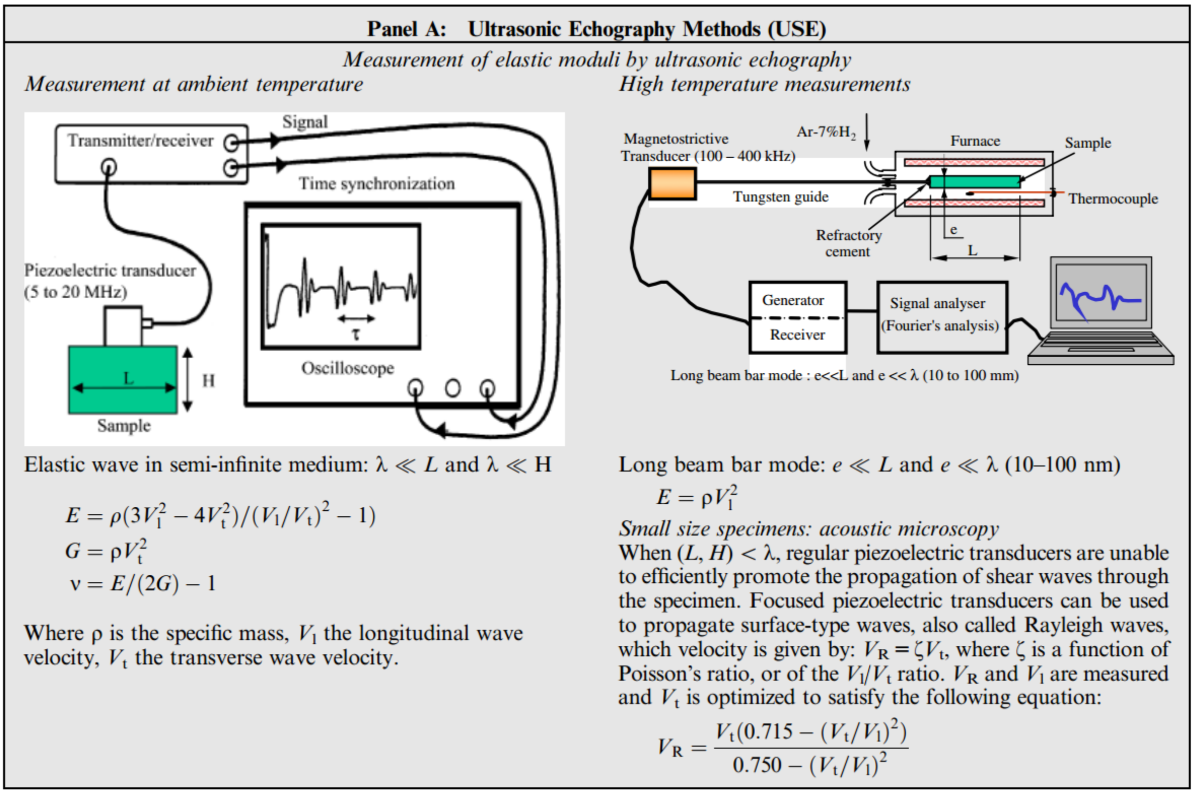
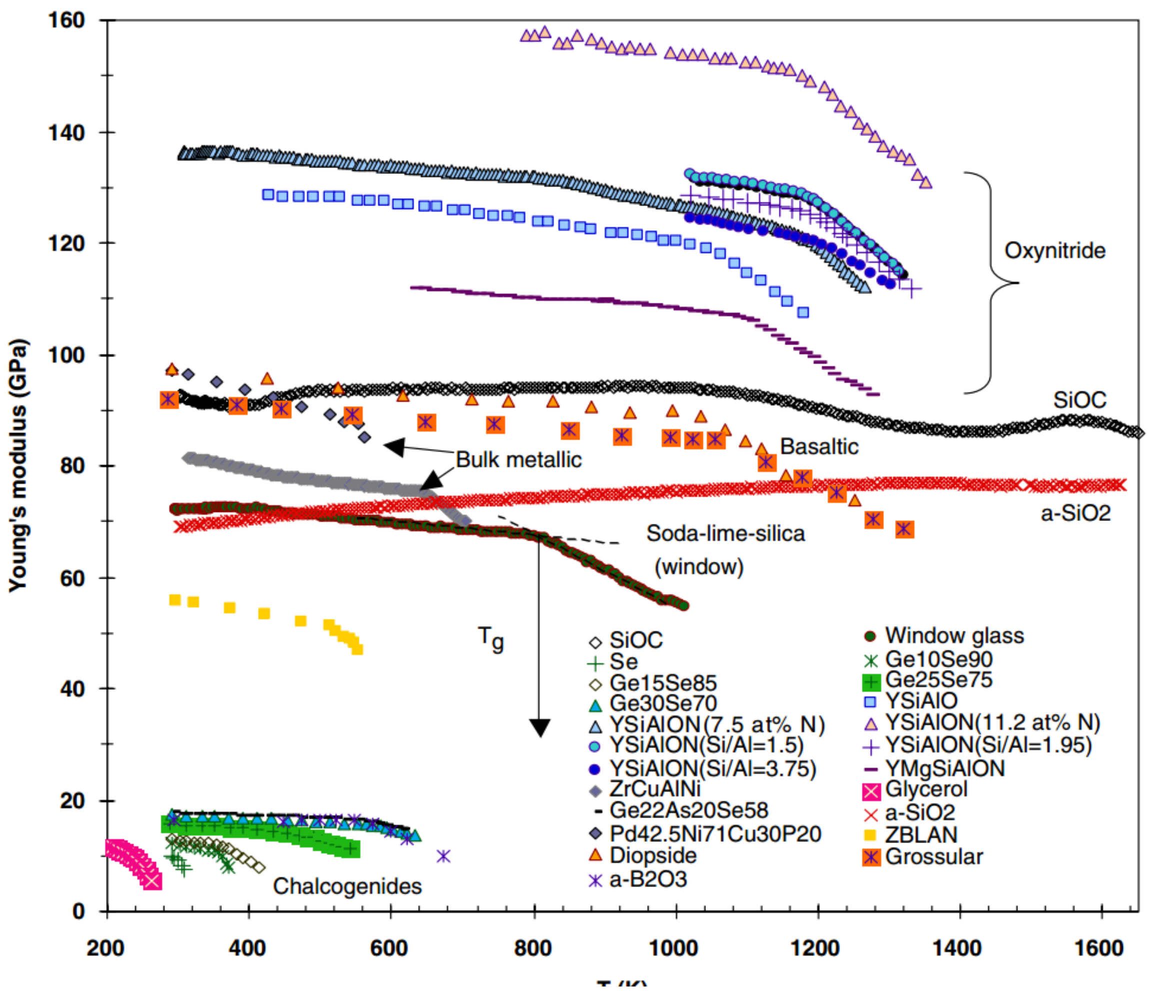
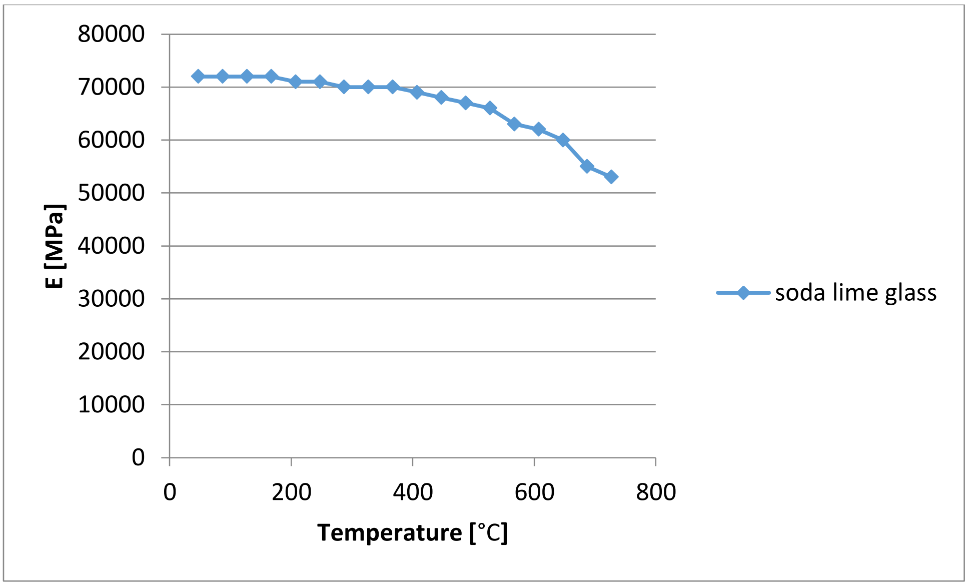


Figure 3.10 Ultrasonic echography (source: Elastic Properties and Short-to Medium-Range Order in Glasses by Tanguy Rouxel)



Graph. 3.8 Temperature dependence of Young's modulus for various glass types (source: Elastic Properties and Short-to Medium-Range Order in Glasses by Tanguy Rouxel).



Graph. 3.9 E modulus soda lime glass

3.2 Glass Production

3.2.1 Float Glass

Nowadays, most of the glass types are produced by float manufacturing process. The Pilkington Brothers mentioned some important advantages of this process in 1959:

- Low cost
- Wide availability
- Good quality of glass
- Possibility to produce large glass panes

In addition to mass production, flat glass often needs to be further developed. This post processing determines the shape, characteristics, properties etc. of the final product.

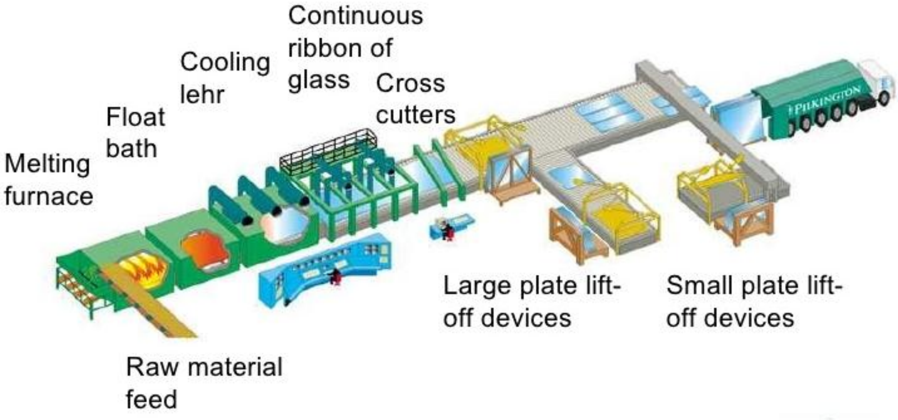


Figure 3.11 Float glass process (source: www.plikington.com)

3.2.2 Glass Tempering or Heat Treatment

After float process glass should be treated thermally; this improves the safety capacity of glass. The concept of this treatment is based on distribution of internal stress in the glass layer. "The idea is to create a favorable residual stress field featuring tensile stresses in the core of the glass and the compressive stresses on and near the surface. The glass core does not contain flaw and therefor offers good resistance to tensile stress". (Haldimann, 2006)

The glass needs to be heated to approximately 700 °C, in order to be toughened. Furthermore float glass should be cooled by cold air. Depending on the cooling speed, two types of toughened glass can be produced: fully tempered and heat strengthened glass.

3.2.3 Fully Tempered Glass

"During the thermal tempering process, float glass is heated to approximately 620−675 °C (about 100 °C above the transformation temperature) in a furnace and then quenched (cooled rapidly) by jets of cold air." (Haldimann, 2006). This glass type has a high tensile strength. Moreover, fully tempered glass has the ability of shatttering into millions of small pieces. The dimensions of these pieces are approximately 100 mm2, which has relatively no or small damage effect. It should be mentioned that this glass pieces can be dangerous too, if they fall from a high distance. That is why this glass category can be named relative safe glass type for building industry applications. "In addition the number of cracks that form on failure are directly related to the strength of the glass, the stronger the glass, the more cracks. This results in a problem if the glass is too strong. If the glass panels fail at too high a failure stress, so many cracks form simultaneously that the stress cannot go from one layer to another layer. The structure will then fail because the glass panels in the laminate do not have enough cohesion to take the shear stresses between the tensile zone, where the reinforcement operates, and the compression zone where the cracked glass carries the compression stresses". (F. Veer 2005) Therefore use of fully tempered glass for laminated cases are limited.

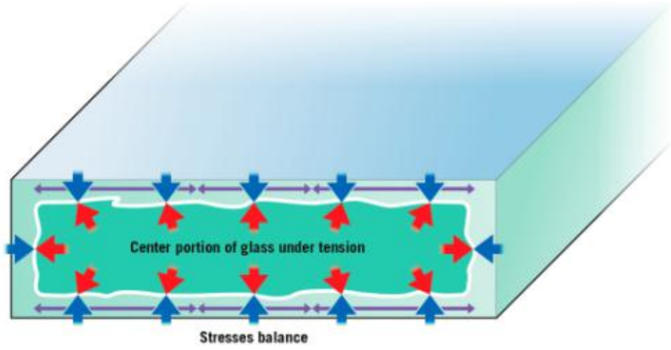


Figure 3.12 Fully tempered glass (source: www.educationcenter.ppg.com)

Figure 3.13 Fully tempered glass (source: www.glassdynamics.com)

3.2.4 Heat Strengthened Glass

"Heat strengthened glass is produced using the same process as for fully tempered glass, but with a lower cooling rate. The residual stress and therefore the tensile strength are lower. The fracture pattern of heat strengthened glass is similar to annealed glass, with much bigger fragments than for fully tempered glass. Used in laminated glass elements, this large fracture pattern results in a significant post-breakage structural capacity". (F.Veer 2014)

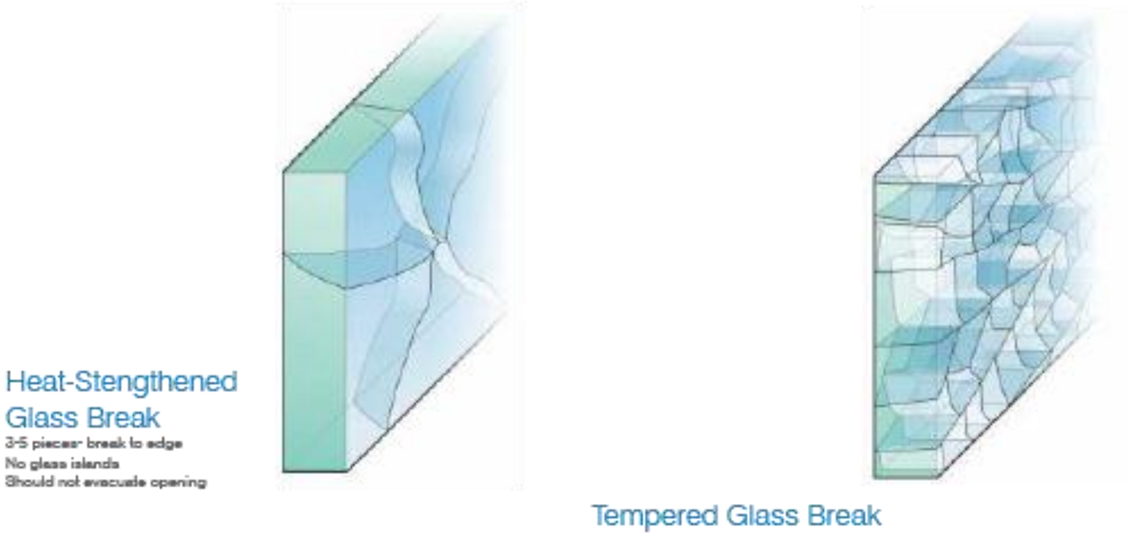


Figure 3.14 Heat strengthened glass vs fully tempered glass (source: www.dutchglass.in)

3.3 Structural Glass

This section takes a look at possibilities of glass as a structural element. The current products will be reviewed.

3.3.1 Laminated Glass

Different types of adhesives are available on the market. They are polymer materials, which are used to laminate glass layers. They can be classified based on the thermos mechanical properties.

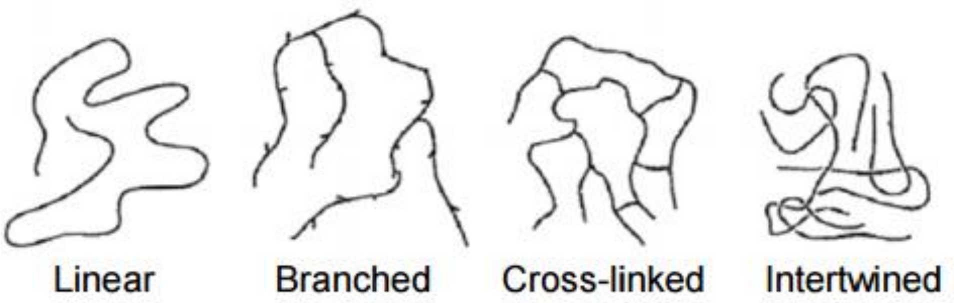


Figure 3.15 Molecular structure of polymer (source: http://www.ct.upt.ro/)

- “Thermoplastics: Relatively weak intermolecular forces hold molecules together in a thermoplastic. The material softens when exposed to heat, but returns to its original condition when cooled. This can be repeatedly softened by heating and then solidified by cooling, for improved performance.
- Elastomers: Rubbery polymers that can be stretched easily to several times their unstretched length and which rapidly return to their original dimensions.
- Termosets: Solidify or “set” irreversibly when heated and further heating cannot reshape the material”(source: http://www.ct.upt.ro/).

Polymer adhesives

Thermoplastics	Elastomers	Thermosets
Linear or branched polymer chains	Long cross-linked polymer chains	High cross-linked polymer chains
PVB	Silicone (inorganic) Polyurethane (organic)	Acrylic adhesive Polyester resin, Epoxy

Table. 3.3 Different types of polymer adhesives (source: http://www.ct.upt.ro/)

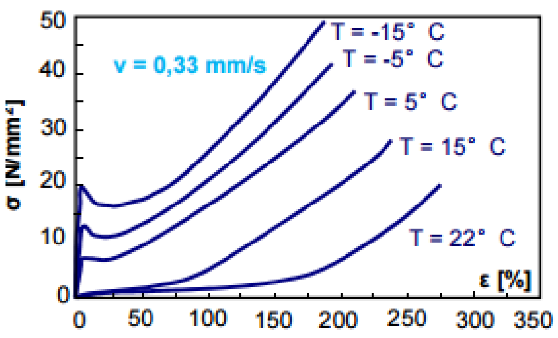
Types of interlayers

Two or more of glass layers are glued together by an in between layer (interlayer). Possible types of interlayers are:

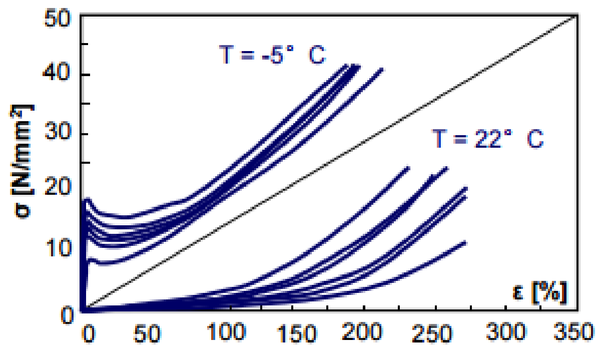
- Polyvinyl butyral (PVB)
- Ionoplast Polymers
- Ethylene Vinyl Acetate (Cross-Linked EVA)
- Cast in Place (CIP) liquid resin
- Thermoplastic polyurethane (TPU)

Polyvinyl butyral (PVB)

- “Blocks UV almost completely
- Interlayer = 2 or 4 foils (1 foil= 0.38mm)
- Requires special storage climate controlled conditions
- Can be used with other interlayers and colors
- Viscoelastic (properties depend on the temperature and load duration)
- Best performance at low temperatures and for short loading times (if not, shear resistance is greatly reduced)” (source: http://www.ct.upt.ro/)



Graph 3.1 PVB properties paet1 (source: http://www.ct.upt.ro/)



Graph 3.2 PVB properties paet2 (source: http://www.ct.upt.ro/)

Properties	Symbol	unit	value
Density	p	Kg/m^3	1070
Shear modulus	G	GPa	0-4
Poisson's radio	v	-	$\sim$ 0.50
Coef. Thermal expansion	α_T	K^{-1}	80.10^{-6}
Tensile strength	f_T	MPa	> 20
Elongation at failure	ε_t	%	>300

Table. 3.4 PVB properties (source: http://www.ct.upt.ro/)

Ionoplast Polymers

Ionoplast Polymers are composed from ethylene and metha-crylic acid. Sentry glass is example of this products which is available on the market. Sentry glass can make laminate 100 times more rigid than laminate with a PVB foil. However this is not valid at all temperatures. It has an excellent adhesion on metal coated glass' surfaces. Moreover it is transparent without high haze index. But its price is high and it is not easy to trim after cure. It should also be mentioned that this cannot be used with other kind of interlayers.

Ethylene Vinyl Acetate

Advantages:

- "EVA is the copolymer of ethylene and vinyl acetate, typically contains 26% Vinyl Acetate.
- Very good sound insulating properties in the high frequency range.
- It is the dominant photovoltaic encapsulant.
- Highly adhesive to materials other than glass, thus it is used for connections and glued supporting structural details, such as point fixed glazing systems.
- Outstanding heat, humidity and ultraviolet ray durability and long-term reliability
- Today's EVA films provide optical quality that can rival PVB"

Disadvantages:

- "Haze level worse than PVB

- Higher Yellowness Index (YI) than PVB
- Lower impact performance than PVB (< 50% of PVB strength of the same thickness)" (source: http://www.ct.upt.ro/)

Cast in Place (CIP) liquid resin

Advantages:

- "Typical base polymers for this type of lamination are acrylics, polyurethanes and polyesters
- Belong to the Thermosetting Plastic family (polymer material that cures irreversibly).
- Allows for a wide variety of thickness and designs
- Can be colored with dyes or pigments, although pigmented versions have higher haze than PVB
- Low capital investment (relative to autoclave lamination)
- Free flowing ; can adapt to most shapes (bent/curved glass)"

Disadvantages:

- "Poor optics due to variations inlazing thickness
- Poorer low temperature impact versus PVB laminates
- Chemical handling requires permits
- Edges retain tape and must be cut off if exposed
- Cannot provide BOTH good acoustics and impact
- Lower output / Productivity – High manufacturing costs" (source: http://www.ct.upt.ro/)

3.3.2 Armored Laminated Glass

Using armored laminated glass is a method for increasing the residual stability. A layer of armor between the glass layers between the glass layers needs to be added. The composition of an armored laminated glass structure is presented in the following pictures." The armor is needed because of the low bending strength and load-bearing capacity of the broken glass pieces. Although a high tensile stress is required of the armored elements, it is also important that they are very thin so as not to disrupt the transparency of the object. Research has found that the best reinforcing elements are meshes made of stainless steel wire or high-strength springs. Another option is embedding glass-fiber or carbon-fiber products into the PVB layers"(Kaltenbach, 2004).

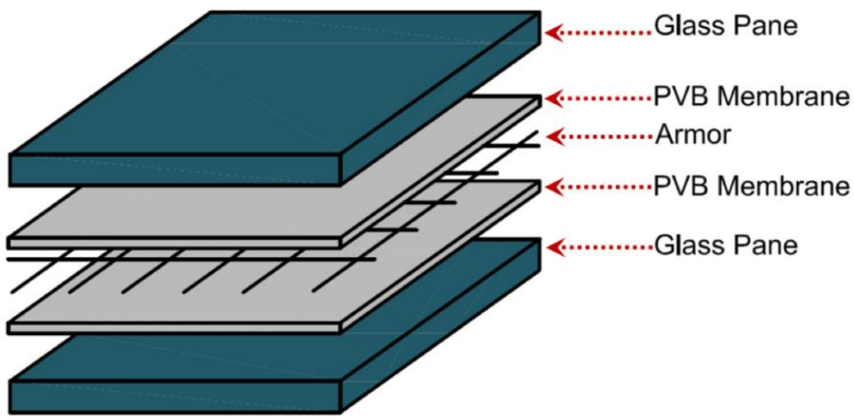


Figure 3.16 Amored laminated glass

3.3.3 Steel Reinforced Glass

A steel reinforcement at the top bottom (tension zone) of laminated glass beams should be placed. This reinforcement helps glass to obtain tensile strength, can be applied to laminated glass. Several steel reinforced glass' tests were performed at TUDelft (Louter, 2011). Test results show that a reinforced glass beam has some load bearing capacity after the failure.

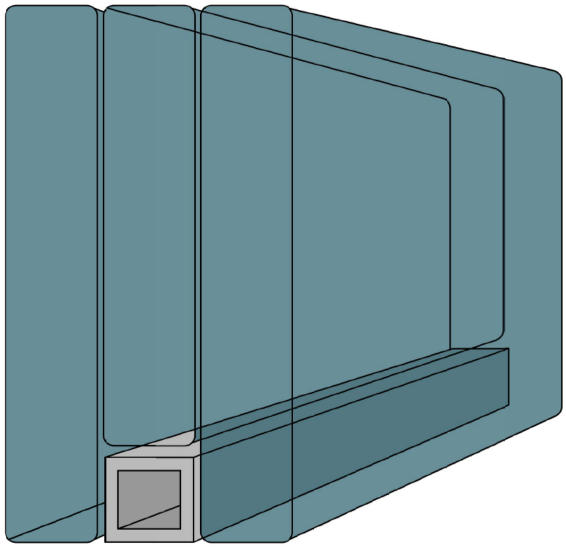


Figure 3.17 Steel reinforced glass

Figure 3.18 Steel reinforced glass (source: Dr. Louter Tests)

3.4 Conclusion

As it mentioned before, it is essential to have sufficient knowledge about glass as a material and its properties. For this reason a literature study is done on the current glass material products and its properties. The results of this studies show that soda lime is the type of glass which is mainly used for usual construction application. But borosilicate glass is a more proper choice for fire resistance glazing; because it is more resistant for temperature changing. The other mentioned glass type are not proper for building industry. Dr. Louter used soda lime glass for his tests at Empa. It is for this reason that, soda lime's properties will be considered for the finite element modeling. This model is discussed in the following chapter in more details.

Moreover thermal and mechanical properties of glass are determined. Results of these studies show that all glass properties depend on temperature. Moreover most of the obtained data are from old books, which means there is no sufficient updated information available regarding the glass properties at high temperature. This may cause some differences between finite element model and test results.

Furthermore the possibilities of glass as a structural element were reviewed. The following table shows the characteristics of annealed, heat strengthened and fully tempered glass. In order to achieve sufficient tensile bending strength and proper failure behavior, the heat strengthened glass can be an applicable option for laminating structural glass..

Characteristics	Annealed	Heat strengthened	Fully tempered
Compressive strength [MPa]	200	200	200
Tensile strength [MPa]	45	70	120
Type of fracture	Large and sharp	Small and softer	Very small
Cost	low	high	high

Table. 3.5 Characteristics of annealed, heat strengthened and fully tempered glass

4 Finite Element Model for Empa Tests

In the following paragraphs the structural analysis will be explained. Firstly, the modeling and the load calculation will be presented and following, the analysis results.

4.1 Geometry and Boundary Conditions

Dr. Louter's test data were used for making the geometry in the Finite Element Model (DIANA). The Auto Cad drawing shows that the beam's geometry and its boundary conditions.

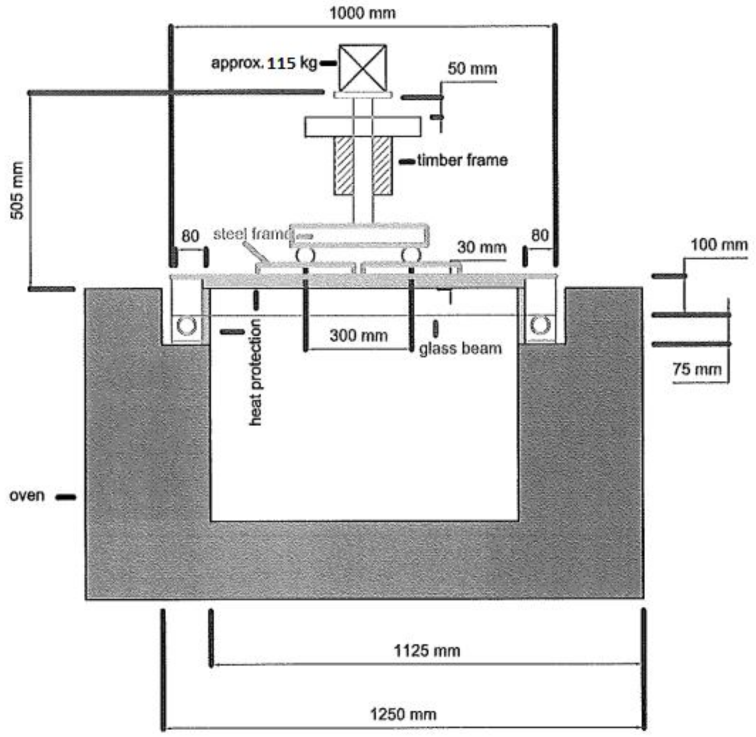


Figure 4.1 Empa test setup (source Dr. Louter drawings)

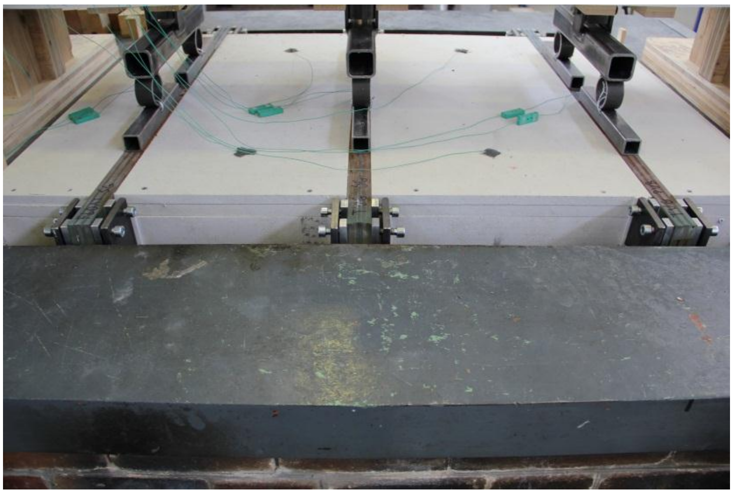


Figure 4.2 Testing laminated glass beams at Empa (Source: Dr. Louter photos)

As first step, a laminated beam model was made in DIANA. This beam consists of 3 soda lime glass layers (10 mm) and two sentry glass interlayers (1.52 mm). The beam has 1 meter length and 0.10 m height. This is a symmetric beam, so half of the beam was modeled in such way that symmetry was simulated. Boundary conditions were applied in the middle of the beam.

Two supports were added to the beam. The beam's left side has a rol support which means it is free in the x-direction and fixed in the z-direction. This support's condition was given for 80 mm of the beam length, which was also illustrated in the Empa's drawings. But the middle of the beam is fixed in the x-direction. In other words its ux=0.

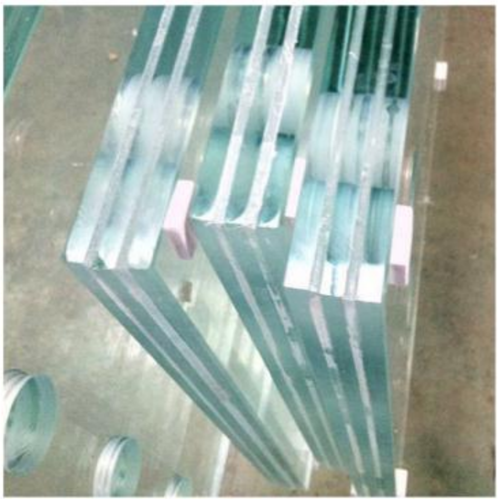


Figure 4.3 Glass beam (Source: http://nl.made-in-china.com)

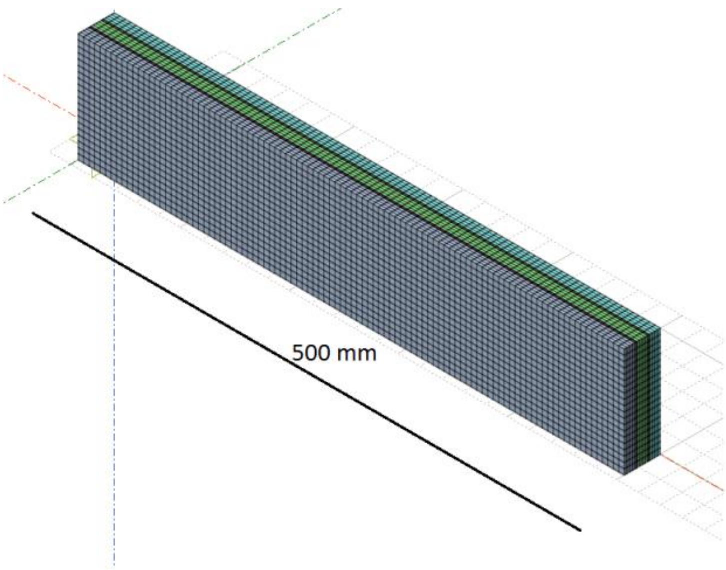


Figure 4.4 3D view beam in DIANA

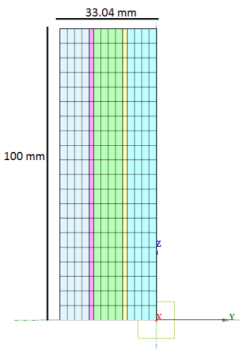


Figure 4.5 Figure 7.4 Cross section beam; 3 glass layer and 2 interlayers

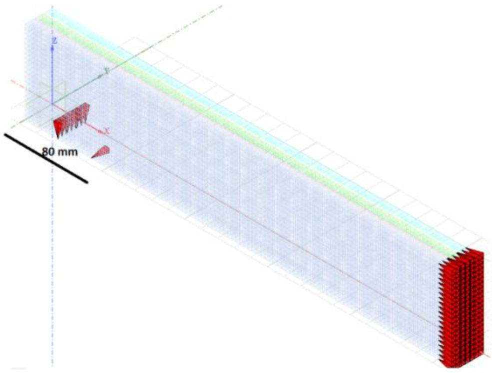


Figure 4.6 Boundary conditions

The Empa's setup drawings show that one steel frames (half beam) is required for placing the mass' load (115 kg) on the beam. Because of this the steel frame was added to the model. This has 250 mm length and its height is 30 mm. There is no connection between glass beam and this frame. It means that the beam and the frame are not glued together. Because of this an interface was considered between this two elements. The vertical loads can be transferred through this interface and the deformation in the x direction is not restricted. In this way the steel frame's function is same as which was during the test.

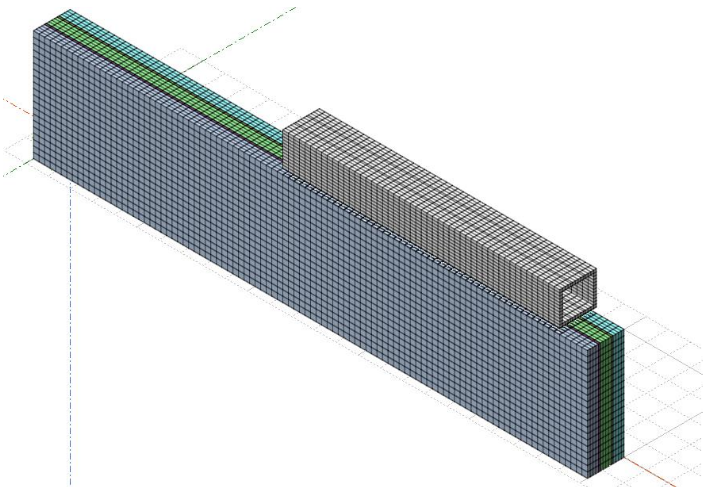
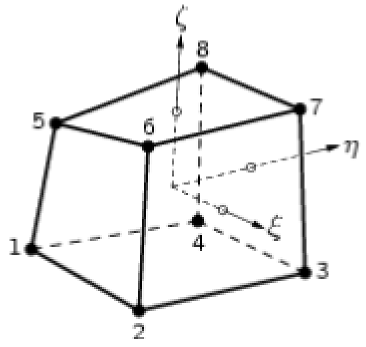


Figure 4.7 Glass beam with steel frame

4.2 Mesh

The element type is used for the glass layers and the interlayers is HX24L. HX24L indicates that it is a 3D brick element with 8 nodes. Its active degrees of freedom is 24 dof's which means 3 dof's ux, uy, uz per node. The element size was set to 20 x 20 x 20 (glass layer) and 20 x 1.52 x 20 mm (interlayer).



Linear 3D brick element **HX24L**
- HX: hexahedron, isoparametric
- 8 nodes, linear
- 24 dof's: 3 dof's ux, uy, uz per node
- L: linear

Figure 4.8 Element type for mesh (Source: www.tnodiana.com)

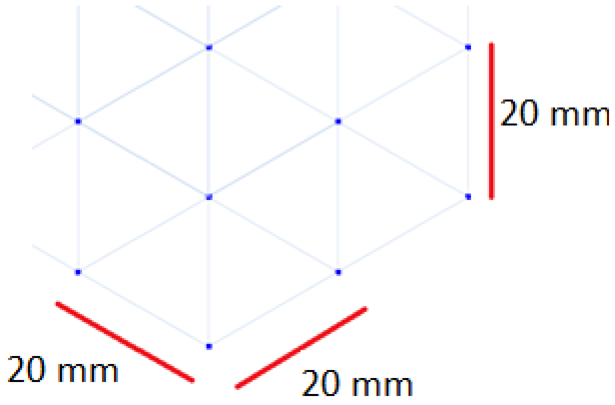


Figure 4.9 Element size glass layer

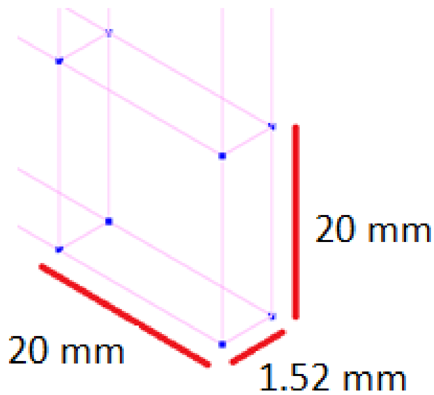


Figure 4.10 Element size interlayer

4.3 Section Properties of the Glass Beams

The material properties of soda lime glass and sentry glass were determined for this stage. Which were presented in the thermal and the mechanical properties' chapter. In addition, the Poisson's ratio of 0.23 and 0.46 are considered for glass and sentry glass at room temperature. The mass density of glass and sentry glass are given 2500 kg/m^3 and 0.95×10^{-6} kg/m^3 respectively.

4.4 Loads

Seven kinds of loads cases were considered for the beam modeling in DIANA.

- mass 115 kg
- beams' self-weight
- oven temperature convection
- oven temperature radiation
- initial temperature
- air temperature convention
- air temperature radiation

4.5 Sensitivity Analysis

In this chapter the sensitivity analysis procedure that has been followed will be explained as well as the goals that have been set for the optimum model.

4.5.1 Main Goals and Strategies

Different thermal and mechanical properties of glass change at high temperatures. For this reason there was need for a risk analysis in order to understand their influences. The properties' changing were added to the model with several steps. Furthermore the results for every step were compared to the Dr. Louter's test. The main goal of this procedure was understanding glass behavior and at the same time making a model which is close to real situation.

4.5.2 Optimum Mesh

The first part of the analysis contains the search of the most optimum mesh. The following graph illustrates the inside temperature of the beam. In particular the red line represents the oven's temperature, the orange one is the test results at Empa, the light blue's line is the model with a mesh of 20 mm, the green one is the mesh of 5 mm and the dark blue color present the mesh of 1.25 mm. It has to be pointed out that the material properties were considered as constant (room temperature values). Figure 4.11 shows the location of the thermocouple, which measured the inside glass temperature.

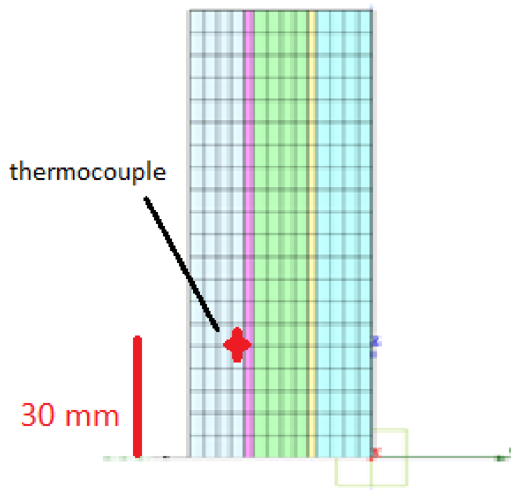


Figure 4.11 Location of measuring point

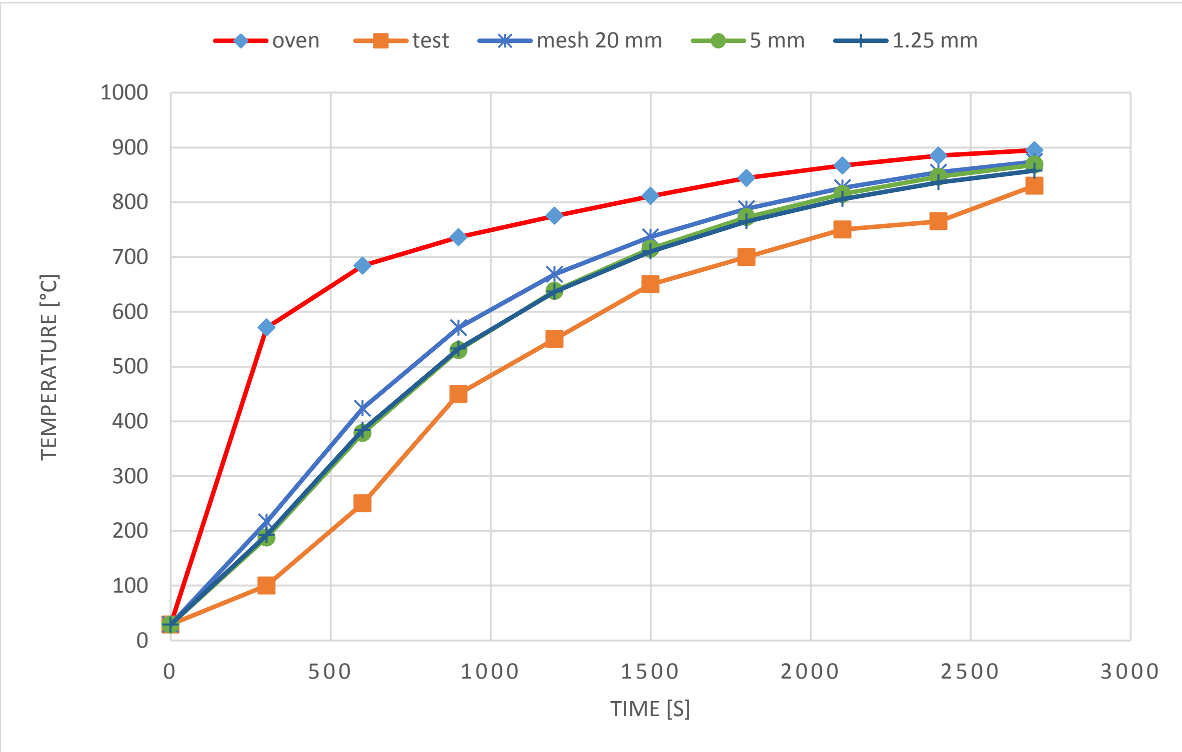


Table. 4.1 Optimum mesh

The graph shows the difference between rough and fine meshing. The mesh of 1.25 mm is more close to the test results. Moreover the results of mesh 5 and 1.25 mm are very close to each other. This means that using mesh finer than 1.25 mm does not result in more exact data. And this will cause more required time for calculation without any advantages. Therefore, the decision is made to consider mesh of 1.25 mm for further modeling.

4.5.3 Changing Thermal Properties

As next step the thermal properties' changings were added to the model. The values used, have been described in the chapter about thermal properties. In the following graphs different checks that took place are presented. It has to be pointed out that the only thermal analyses was made at this stage. So it is not checked if its displacements is complied with the displacements' value from the test.

Thermal Conductivity

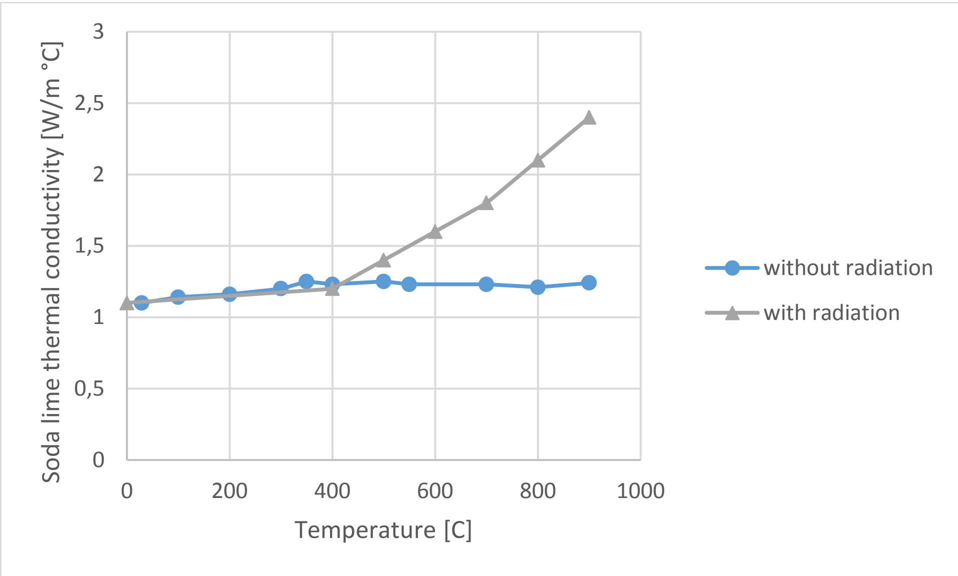
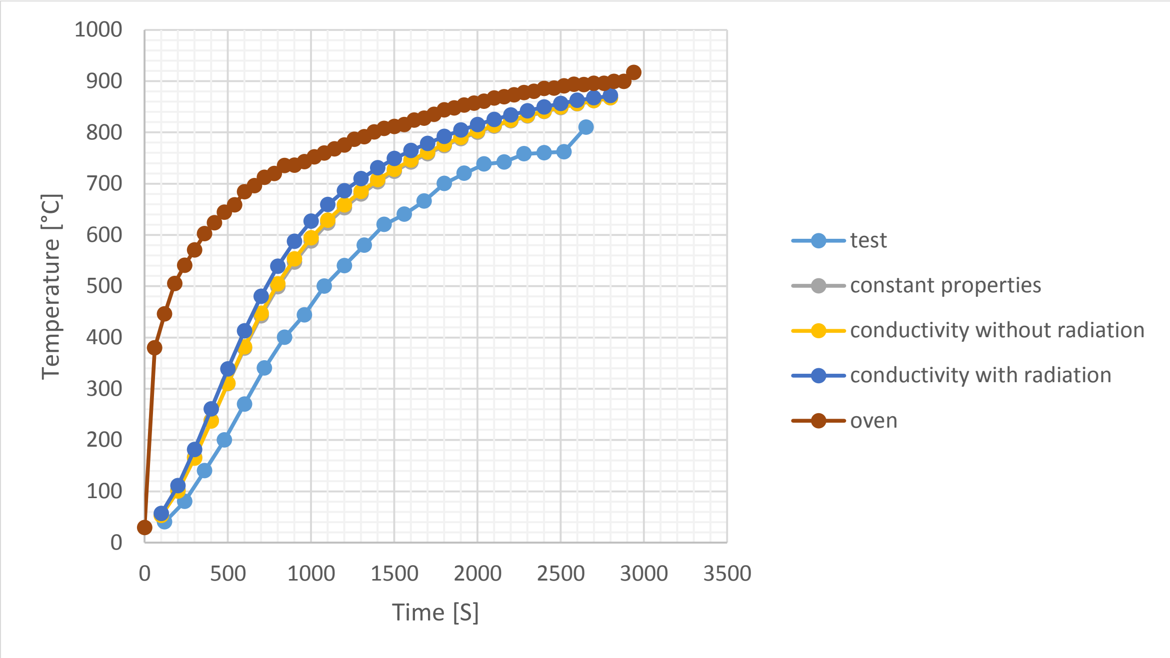


Table. 4.2 Thermal conductivity dependence of temperature. Data on soda lime glass were obtained by Timothy W. Tong (book conductivity 22).

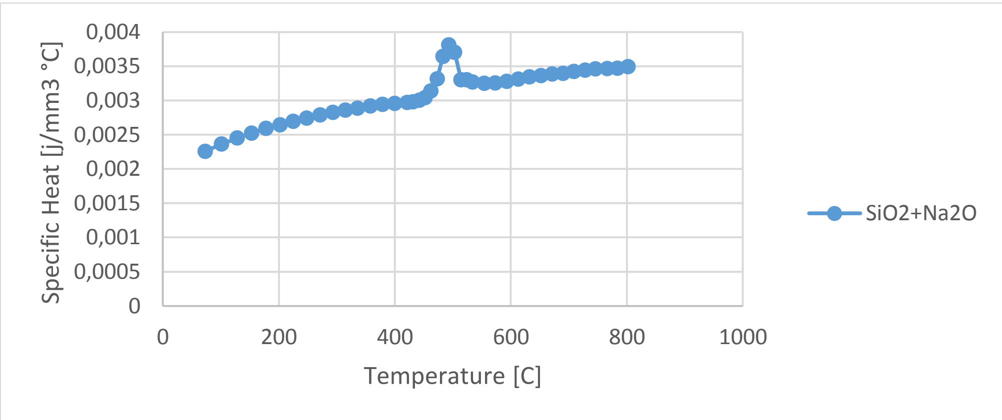
Thermal conductivity values of the Table. 4.2 Thermal conductivity dependence of temperature. Data on soda lime glass were obtained by Timothy W. Tong (book conductivity 22). are added to two separated models. The Graph. 4.1 Glass temperature with constant and thermal conductivity illustrates these two new variants that need to be checked for the thermal properties. In particular the yellow line represents the influence of thermal conductivity without radiation, the blue line thermal conductivity effect with radiation. As can been seen in the graph the conductivity values with radiation resulted in values, that are more close to the test one. However the difference between the temperature values of these two models is very small. Furthermore the model with constant properties is almost the same as the model with radiation. This means the thermal conductivity property has not big influences on the glass temperature.



Graph. 4.1 Glass temperature with constant and thermal conductivity

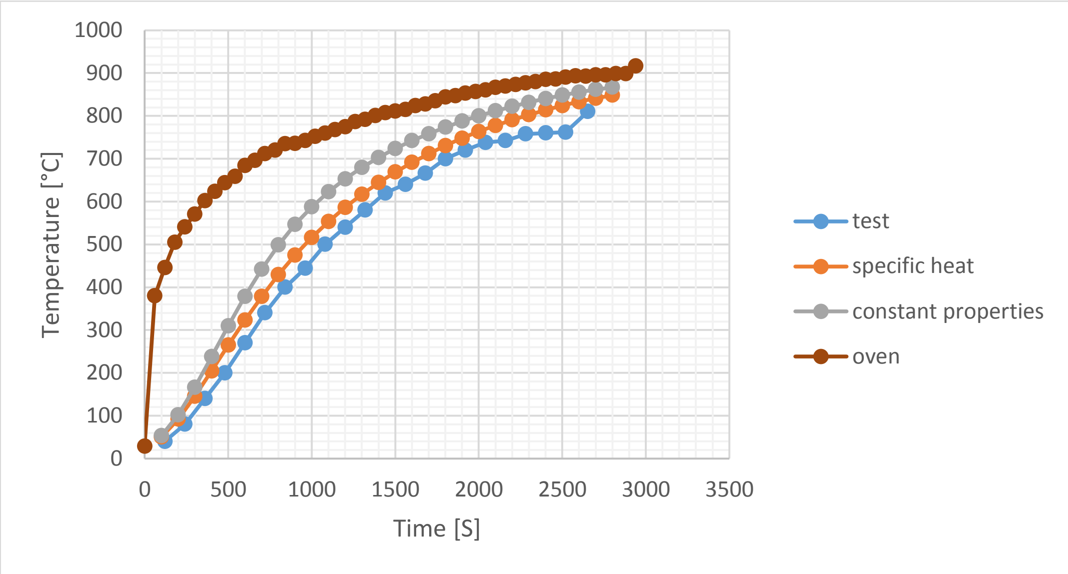
Specific Heat

The specific heat values were obtained from the following graph. This values are used for making a new model.



Graph 4.1 Specific Heat Specific change for SiO_2 & $27.6Na_2O+72.4SiO_2$ (Source: Handbook of Glass Data, Mazurin, Streltsina and Shavaikovskaya, 1983)

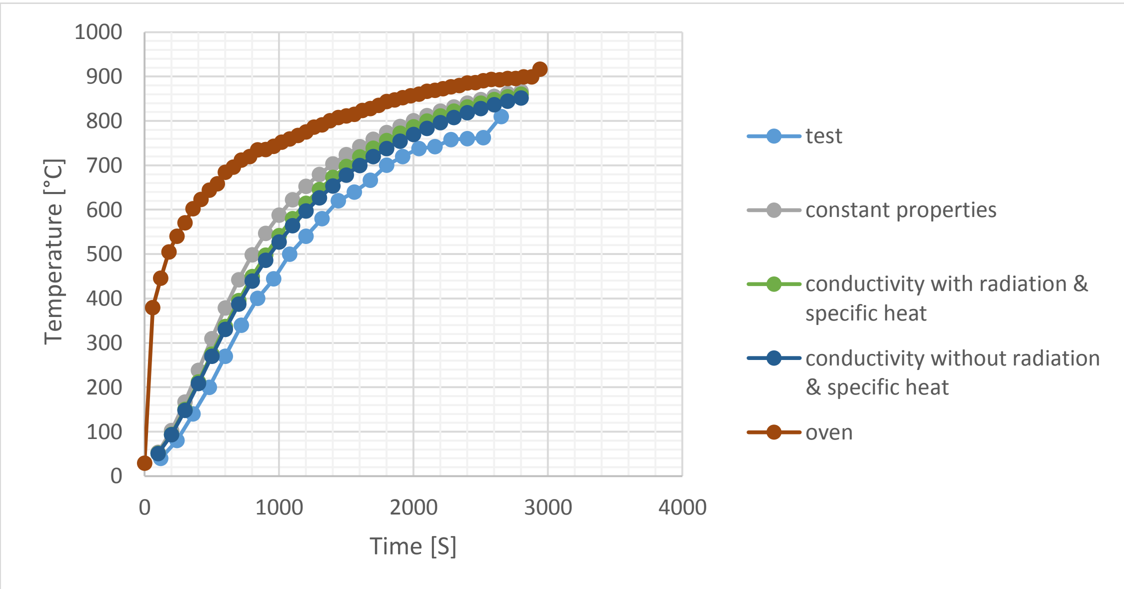
The following graph shows the influence of changing heat specific at high temperature. As can been seen in the graph the heat specific property has considerable influence on the glass temperature. For this reason the temperature results of this model (with heat specific) is not same as the model with constant properties.



Graph 4.2 Glass temperature with constant and specific heat

Thermal Conductivity and Specific Heat

Thermal Conductivity (with and without radiation) and Specific Heat values together were added to the model. The combination of thermal conductivity (without radiation) and the heat specific gives more close results to the test. Furthermore the difference between de model and test line is very small, which means the model gives a correct estimation of the glass temperature.

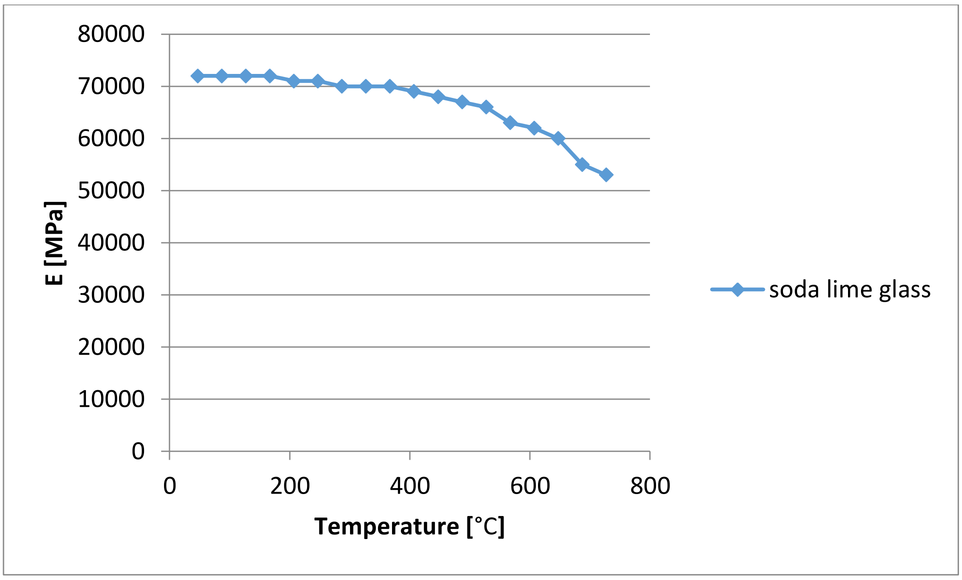


Graph 4.3 Glass temperature with constant, specific heat and thermal conductivity

4.5.4 Changing Mechanical Properties

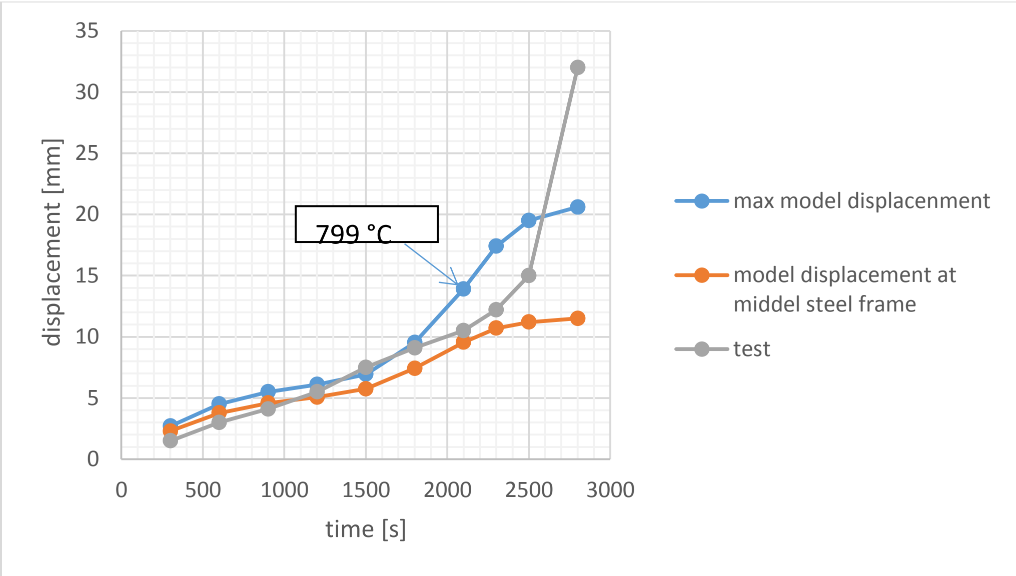
Young's modulus

Dr. Rouxel's graph was added to the model in combination with thermal conductivity (with radiation) and specific heat values from previous graphs. The temperature was not changed, which is logical. , since the young's modulus has no influence on the thermal beam behavior. But E modulus plays an important role for the displacement's behavior of the beam.



Graph 4.4 E modulus for Soda lime glass (source: Dr. Rouxels's paper)

The following graph shows the results for the displacement of the beam. The E modulus obtained from the literature were mostly measured to be around 600 °C. But the highest measured temperature during the test is around 820 °C. Therefore there is a lack of data between 600 and 820°C and, there is a need for making estimations between these two temperatures. This estimation changes the displacement results considerably, which can be seen in the big difference between the grey line and orange line after 2500 seconds. Therefore this is not really possible to make an exact model for this region. However the model shows a correct estimation before this unknown stage. This means the behavior of glass can be predicted correctly where the glass temperature is under 600°C.



Graph 4.5 Deflection test and model results

4.6 Conclusion

The risk analysis showed that the specific heat property has the most influence on the glass temperature. Moreover, deflection results are directly related to the young's modulus input. The young's modulus obtained from the literature were mostly measured to be around 600 degrees. That why making the model for the temperatures higher than 600°C is not possible.

The DIANA model for one of the Empa test shows that the finite element software has the ability for the correct estimation of glass behavior during in fire. However there are some points which need to be considered. The results of literature studies show that most of the glass and the interlayers properties depend on the temperature. Unfortunately there is a lack of data for these properties at high temperature especially for the interlayers. That is why the focus of this thesis is on the single glass form this stage.

5 Tests at Efectis

5.1 Introduction

The experimental tests were performed at the Laboratory of the Efectis Netherlands BV in Bleiswijk. The purpose of this tests was to investigate fire behavior in different glass types. This was done with six series of experiments.

5.2 Test Specimen

5.2.1 Glazing

AGC manufacture was the sponsor for the glass panes. Experiments were conducted for various types; annealed, heat strengthened and fully tempered glazing. The panes had 1.5 m length, 0.3 m width and 0.01m thickness. Before the AGC panels where available, already one test (series1) could be carried out on annealed glass from Zoetermeerse Glashandel B.V, that where of an unknown manufacturer. This changing may cause some differences between test results. Furthermore all used panes were fully polished and grinded (poly slijpen).

Figure 5.1Glass panes before testing in the lab

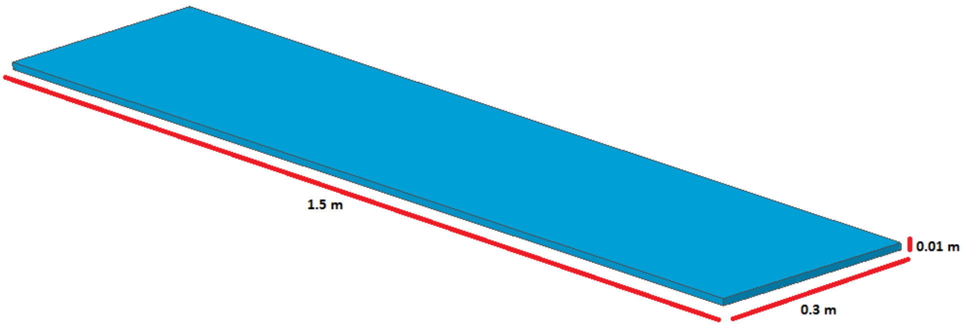


Figure 5.2 Dimension of the glass

Six experiments series are performed during this research. Following table gives an overview for this tests.

Pane number	Factory	Test number	Direction pane	Glass Type	Loads
A	Zoetemeer	1	Lying	Annealed	Self weight+16 kg
B	Zoetemeer	1	Lying	Annealed	Self weight
D	AGC	2	Standing	Annealed	Self weight
E	AGC	2	Standing	Annealed	Self weight
J	AGC	3	Lying	Annealed	Self weight
K	AGC	3	Lying	Annealed	Self weight
N	AGC	4	Lying	Fully tempered	Self weight+16 kg
O	AGC	4	Lying	Fully tempered	Self weight
L	AGC	5	Lying	Heat strengthened	Self weight+16 kg
M	AGC	6	Lying	Heat strengthened	Self weight

Table. 5.1 Panes and tests information

5.2.2 Equipment

Supporting

Two steel supports were used for each pane. Figure 8.3 shows these supports. The right one is a role which means it is free in the x-direction and fixed in the z-direction. But the left one is fixed in both x & z-directions. In other words it is a hinge support.

Figure 5.3 Steel supports

Figure 5.4 Glass panes and steel supports

Thermocouples

In order to collect temperature data, thermocouples were installed at various places on the glass panes. Each of this thermocouples consist of two metal wires. The wires welded together at one point. The temperature is measured at this point. A voltage is created at this point, when glazing temperature changes. Afterwards this voltage is translated to the temperature data in the test results.

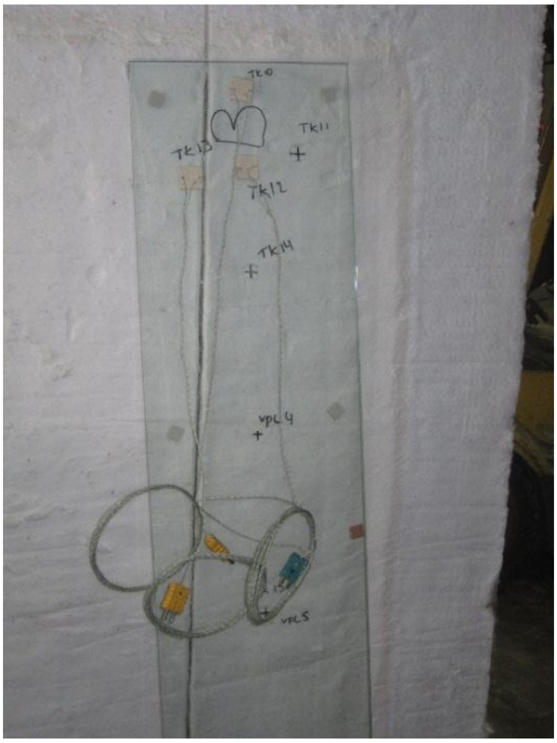


Figure 5.5 Glass and thermocouples

Figure 5.6 Thermocouples

Furnace

Two different furnaces were used for this experiments. Tests series 1 and 2 were performed using square furnace which was 1.22x1.27 meter. Glass panes were located on the top of this one, which means panes were heated only at the bottom side of glass. Test series 3, 4 and 5 were conducted in the bigger furnace, which was 4.0x2.0 meter. The glass panes were placed in the oven, where the specimen were heated from all sides.

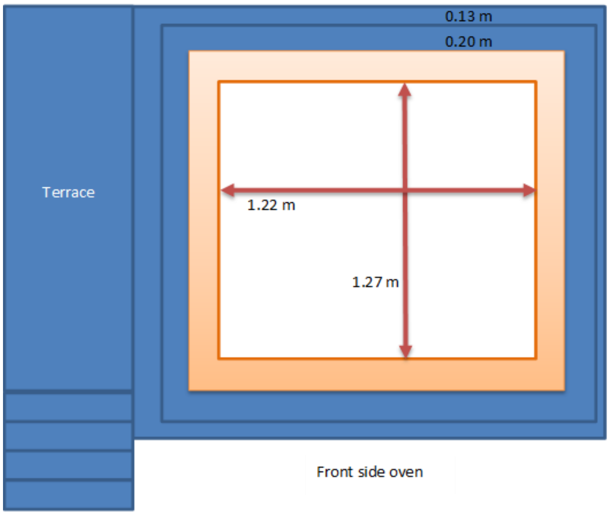


Figure 5.7 Top view small furnace

Figure 5.8 Front side small furnace

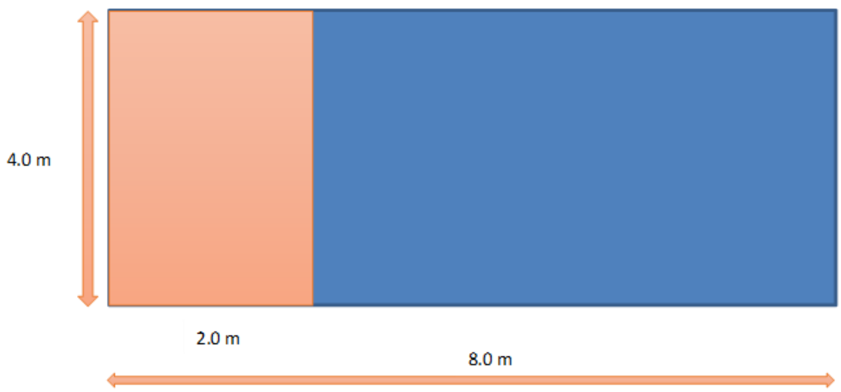


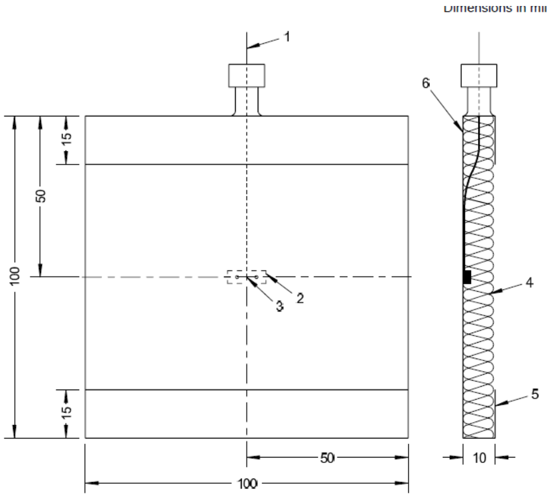
Figure 5.9 Top view big furnace

Figure 5.10 Top side big furnace

Figure 5.11 Outside view big furnace

Furnace Thermocouples

Furnace temperatures are measured by means of thermocouples that are installed at various places in the furnace. “The furnace thermocouples are plate thermometers which consists of a folded nickel alloy plate, a thermocouple fixed to it and insulation material. The folded metal plate should be constructed from a strip of austenitic nickel based superalloy for high temperature oxidation resistance, (150 ± 1) mm long by (100 ± 1) mm wide by (0,7 ± 0,1) mm, folded to the design as shown in Figure 8.10”(NEN-EN 1363-1).



1 sheathed thermocouple with insulated hot junction
2 spot welded or screwed steel strip
3 hot junction of thermocouple
4 insulation material (oriented towards the test specimen)
5 nickel alloy strip (0,7 ± 0,1) mm thick
6 face ‘A’

Figure 5.12 Plate thermometers

Figure 5.13 Location of Plate thermometers; around glass pane

Auxiliary equipment

A computer with measuring software and data logger is needed, which is connected to the thermocouples and deflections measurer for providing temperature and deflection data.

Figure 5.14 Measuring software for small furnace

Figure 5.15 Control room for big furnace

Figure 5.16 Data logger

5.3 Experiment Series 1

5.3.1 Test Setup

This paragraph describes the setup of the first series of the experiments. The annealed panes A & B are tested during this series. In order to work out the details of the experiment, top view and cross sections are drawn in Auto Cad. These drawings were very useful for a good communication with the colleagues at Efectis.

At the beginning there was a plan for testing 3 panes in one series. But the available thermocouples were not enough for measuring three specimen. That is why one part of the furnace is filled with Promatect isolation (yellow area). Each step of test setup process is discussed in the following pages.

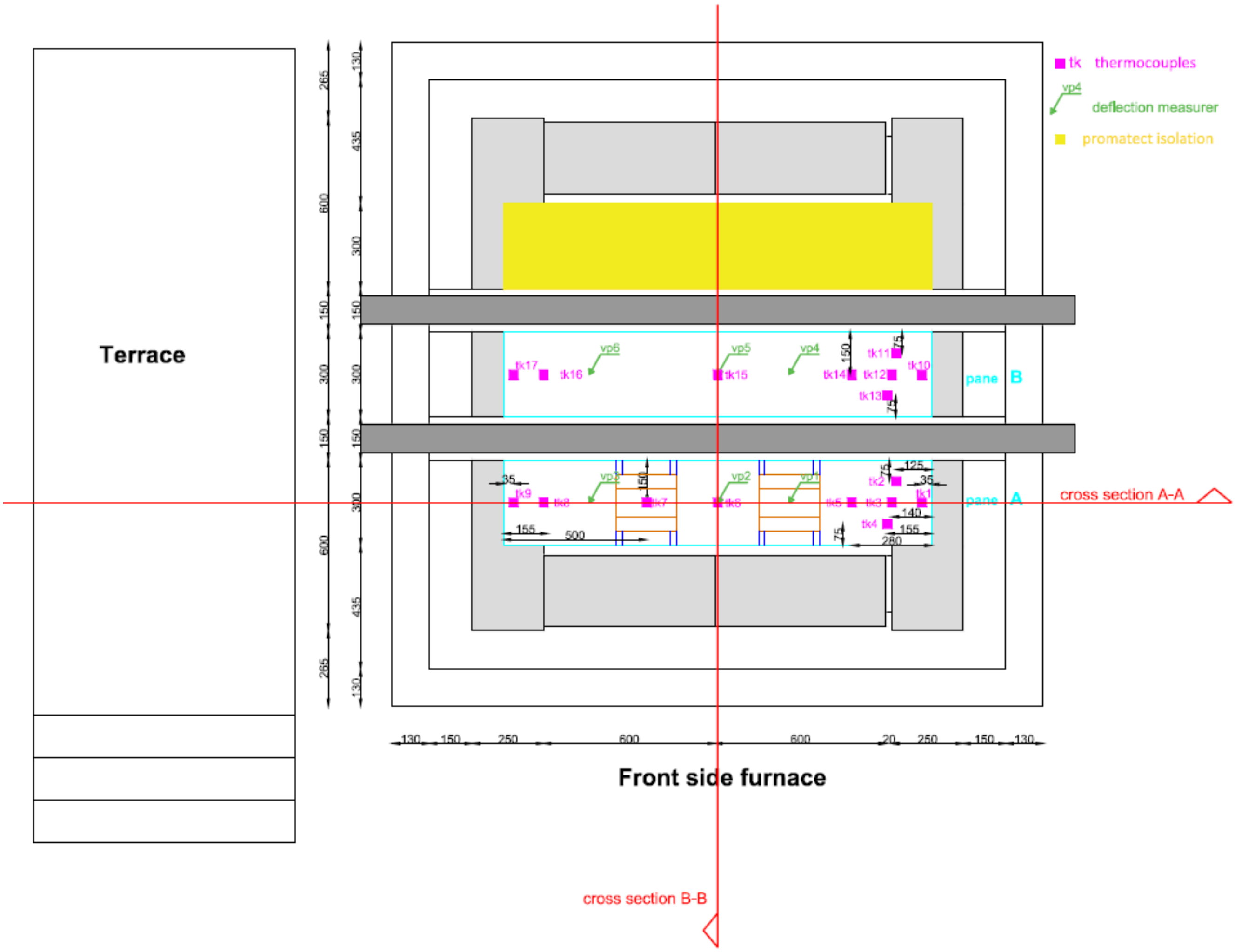


Figure 5.17 Top view Furnace

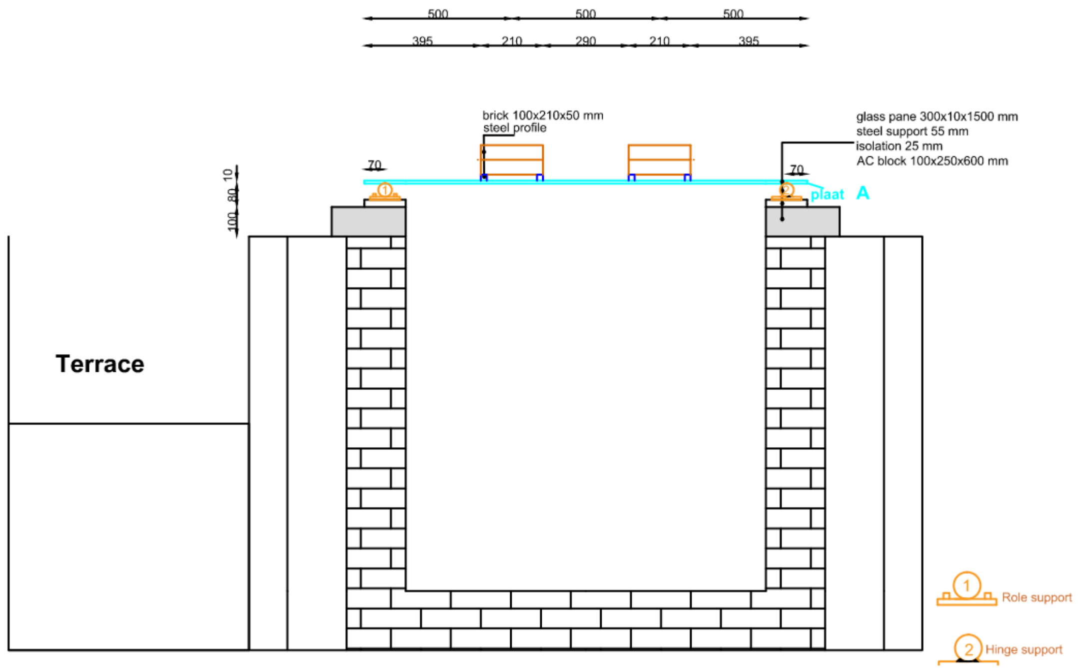


Figure 5.18 Cross section A-A

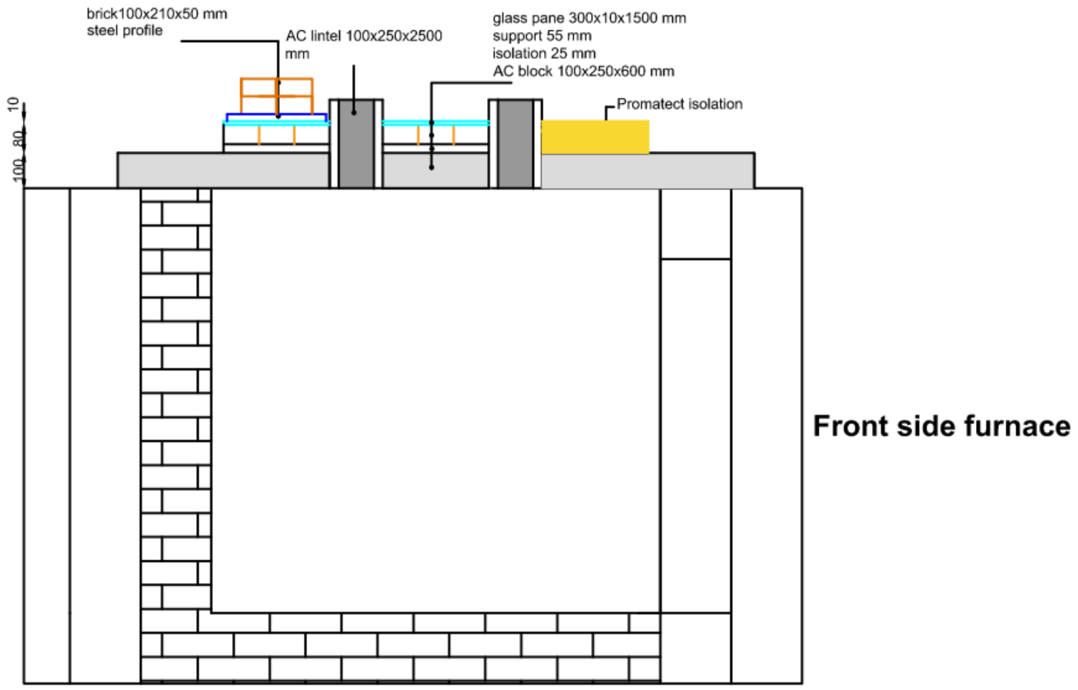


Figure 5.19 Cross section B-B

First of all aerated concrete (AC) blocks are placed on the edges of furnace. This was a good way to prevent the spread of hot air and kept heat inside the furnace. Furthermore the panes had an extra height for deflection in this way.

Figure 5.20 AC blocks placed on furnace edges

Figure 5.21 Top side furnace and AC blocks

The annealed panes A and B are tested horizontally at one time. In order to keep these two panes separately, aerated concrete (AC) lintels are placed between the panes. Moreover these beams prevent the spread of hot air.

Figure 5.22 placing ACC beams at top side furnace

Afterwards the glass panes inclusive thermocouples are placed on steel supports. The spaces around steel supports and between panes and ACC beams are filled with isolation material.

Figure 5.23 Thermocouples installation

Furnace temperatures are measured by means of plate thermocouples that are installed at four places under the panes.

Figure 5.24 bottom view glass panes

In order to have a structural glass, an evenly distributed load is applied on pane A. Eight pieces of bricks (16 kg) are used as load on this specimen, which is 15% of maximum load for an annealed glass. But pane B carried only its self-weight.

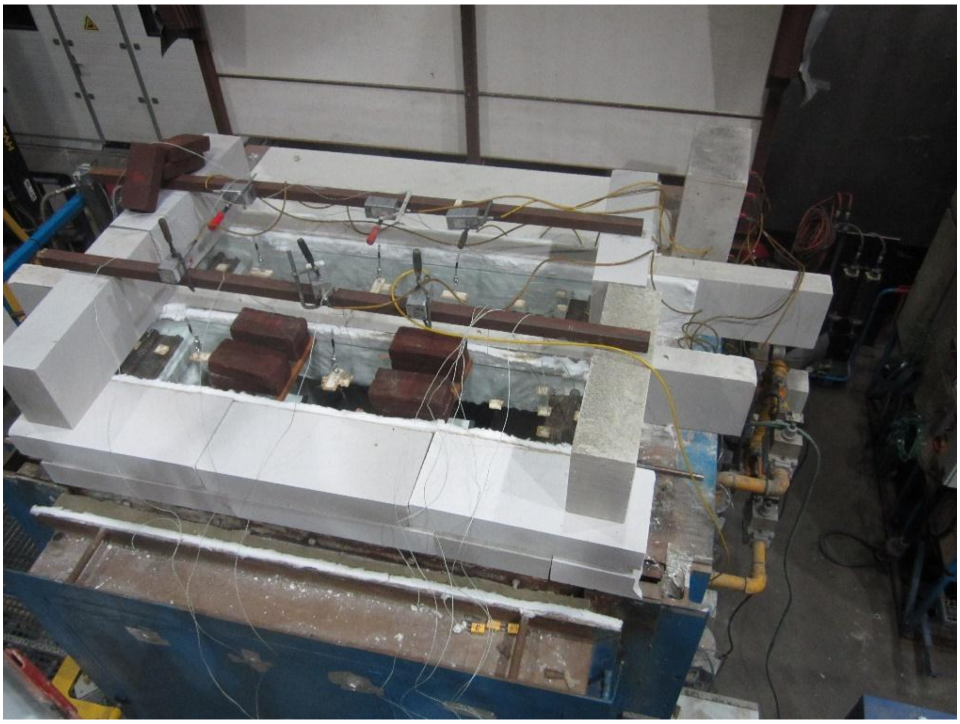


Figure 5.25 Test setup serie1

5.3.2 Furnace Temperature

Plate thermometers measured the furnace temperature at four different places. The graph shows these temperatures. In order to achieve the standard fire curve temperatures, the furnace needs at least five minutes. This test took less than three minutes. That is why the furnace temperature is lower than the standard fire curve especially for TOV1, 2 and 4.

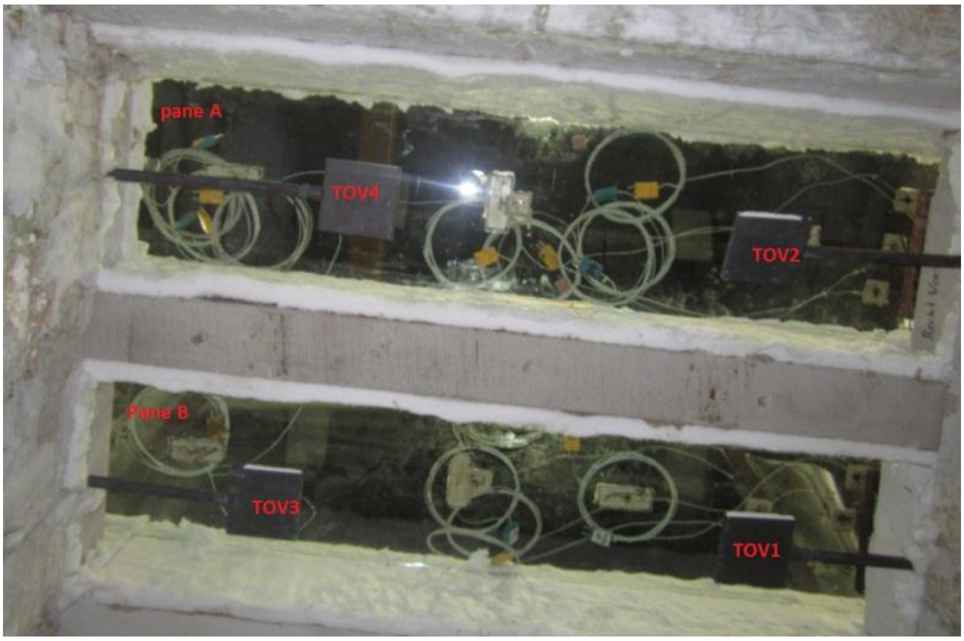


Figure 5.26 location of plate thermometers

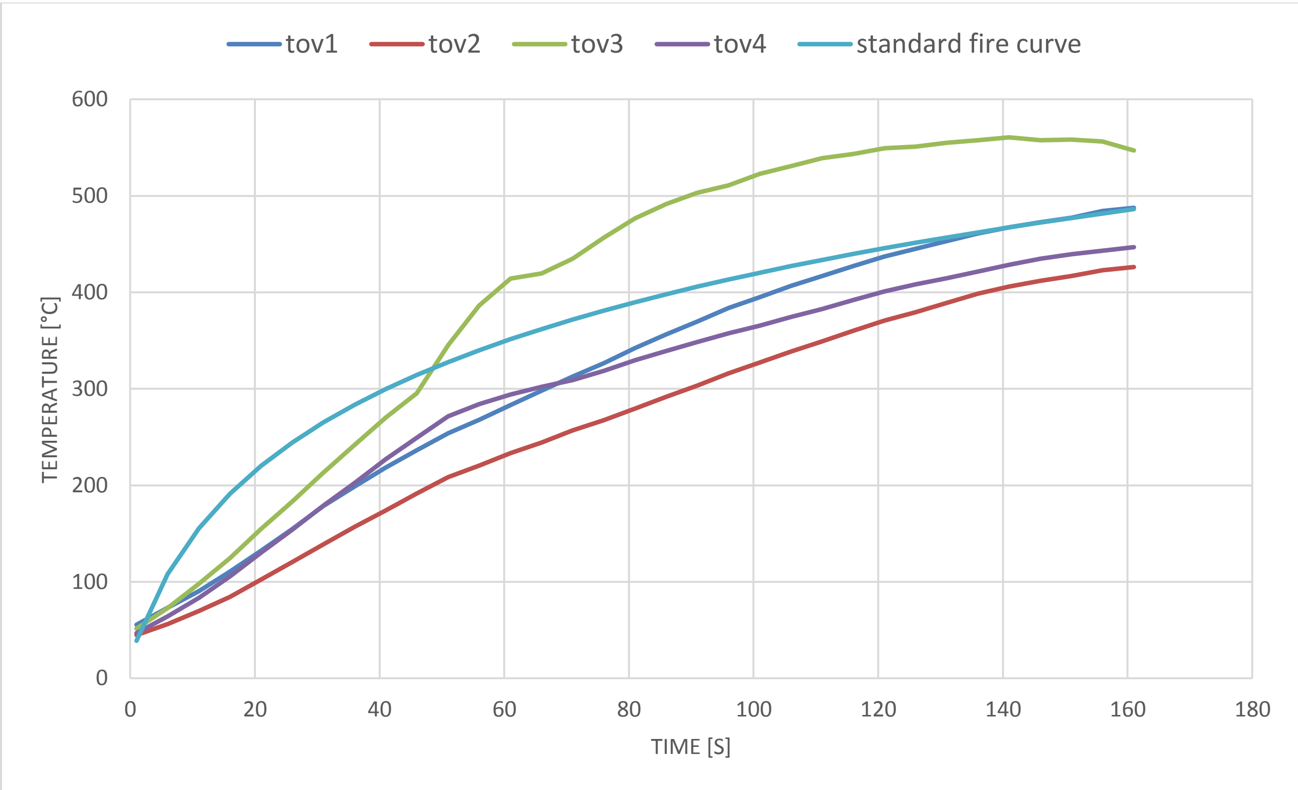


Table. 5.2 Furnace temperature

5.3.3 Pane A

Fracture

Pane A carried a load of 16 kg and its self-weight. This pane is broken after 46 seconds close to left steel support and end part of the pane.

Figure 5.27 pane A before break

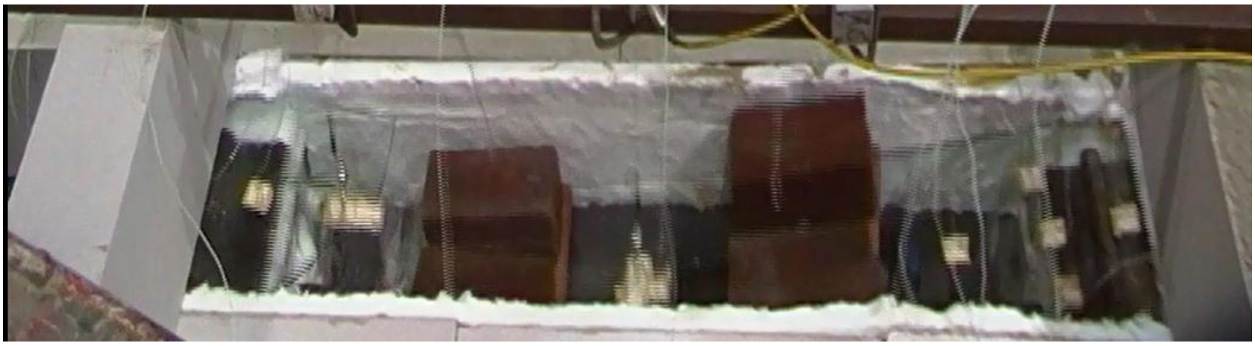


Figure 5.28 pane A during break

Figure 5.29 pane A after break

Figure 5.30 Fracture location pane A

Glass Temperature

Nine thermocouples are installed at various places on the glass surface. The figure shows the location of these thermocouples.

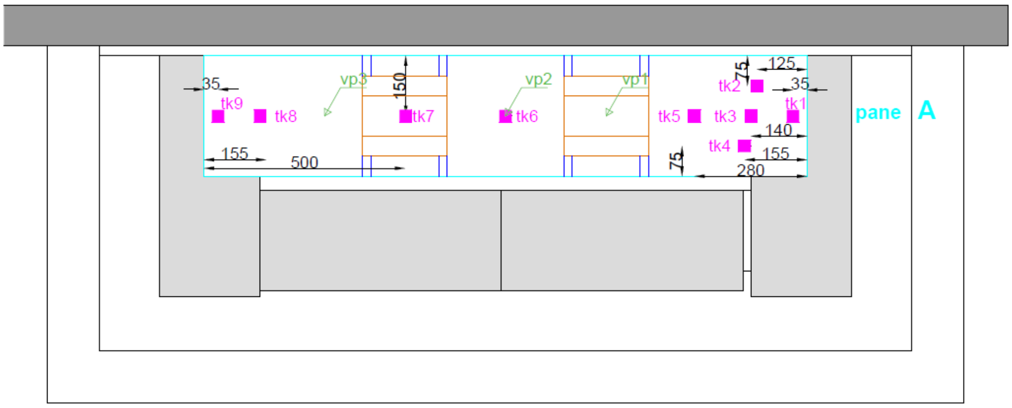
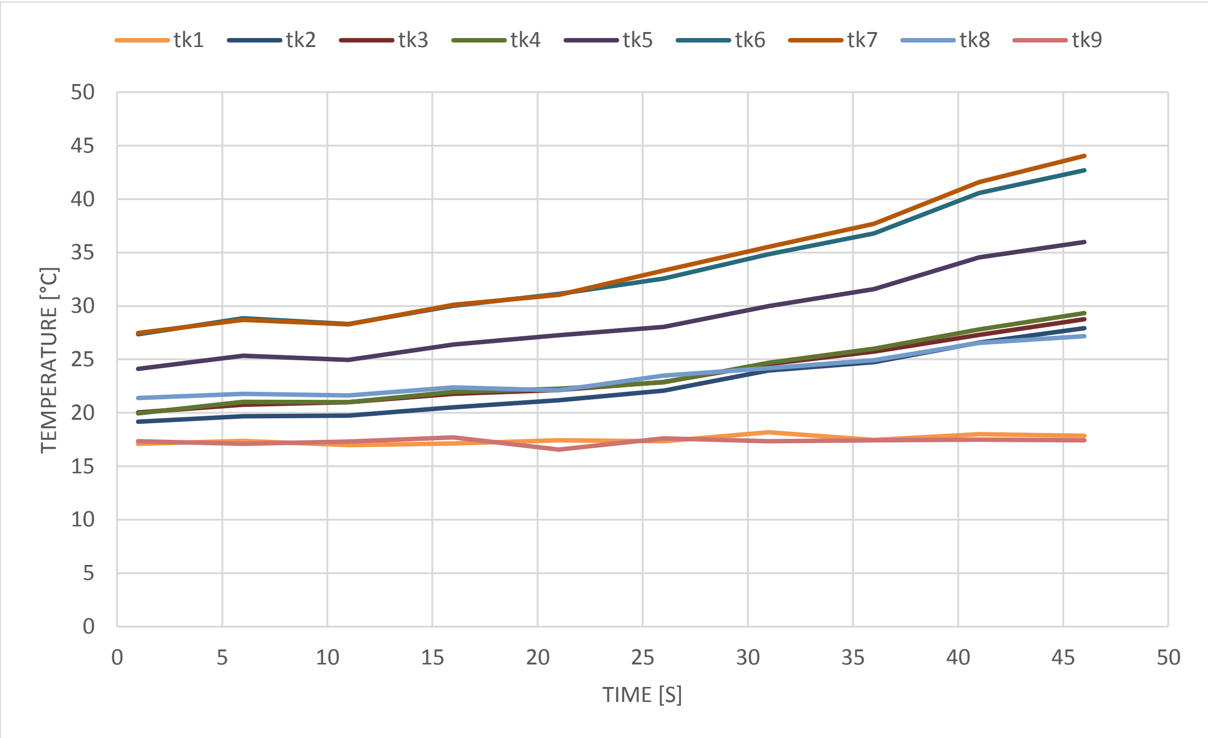


Figure 5.31 setup pane A

The following graph illustrates the temperature data of these thermocouples. The thermocouples number six and seven (tk6&7) recorded the highest temperatures during this test. The maximum temperature on the glass surface was around 45 °C.



Graph. 5.1 Glass temperature A

Deflection

The graph illustrates the test and model deflection results. Unfortunately measurer for defl3 (vp3) did not work during test. That is why no data is availed for its location.

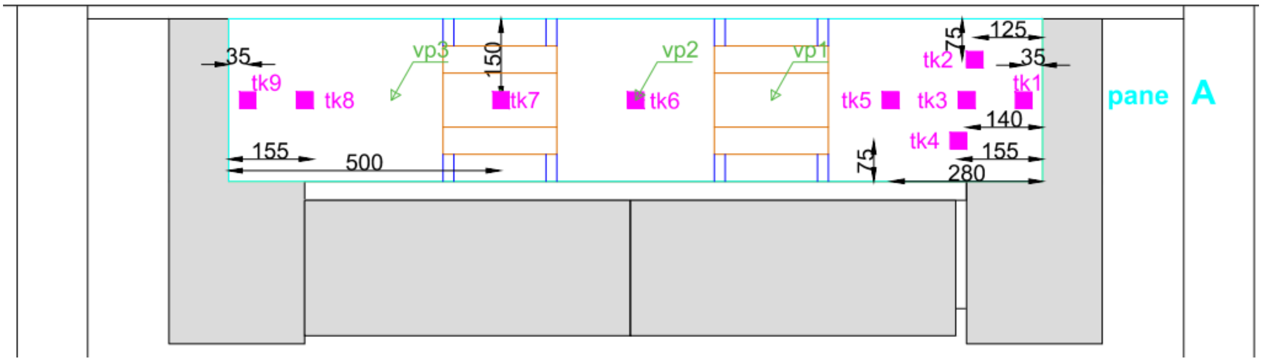
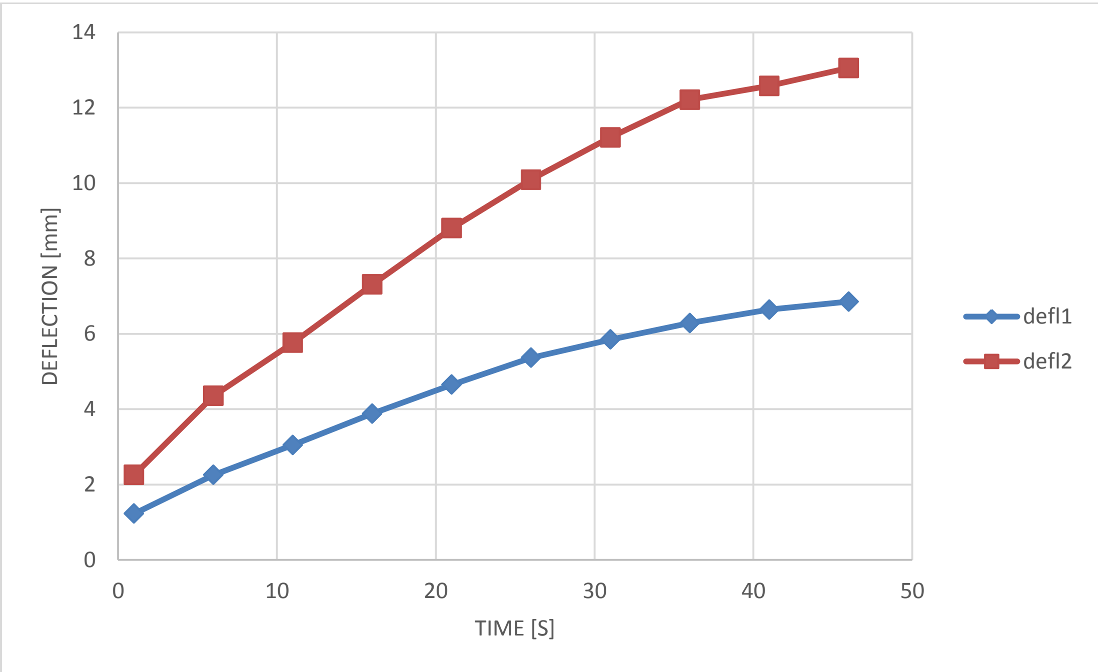


Figure 5.32 Top view pane A



Graph. 5.2 Deflection pane A

5.3.4 Pane B

Fracture

Pane B carried only self-weight. This pane is broken after 126 seconds close to left and right steel supports.

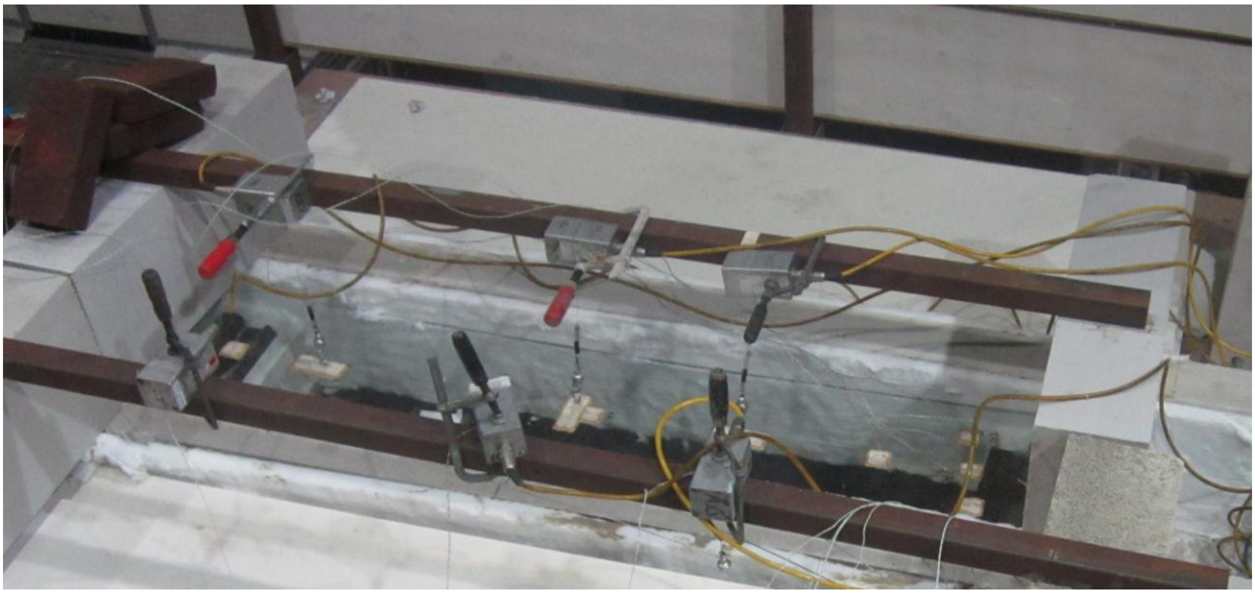


Figure 5.33 Pane B before break

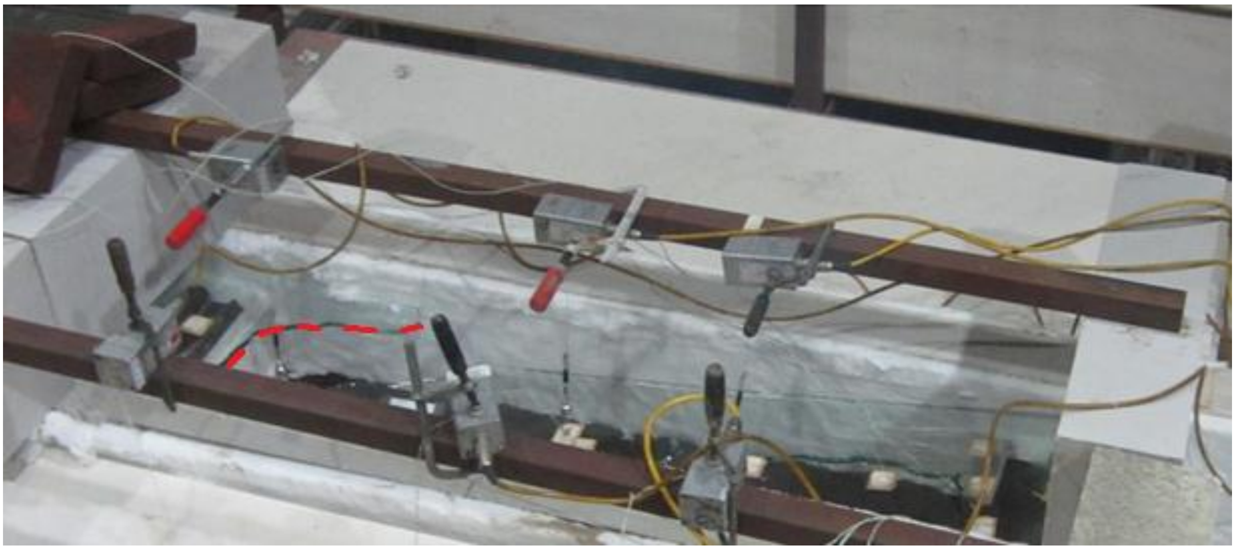


Figure 5.34 Pane B after break

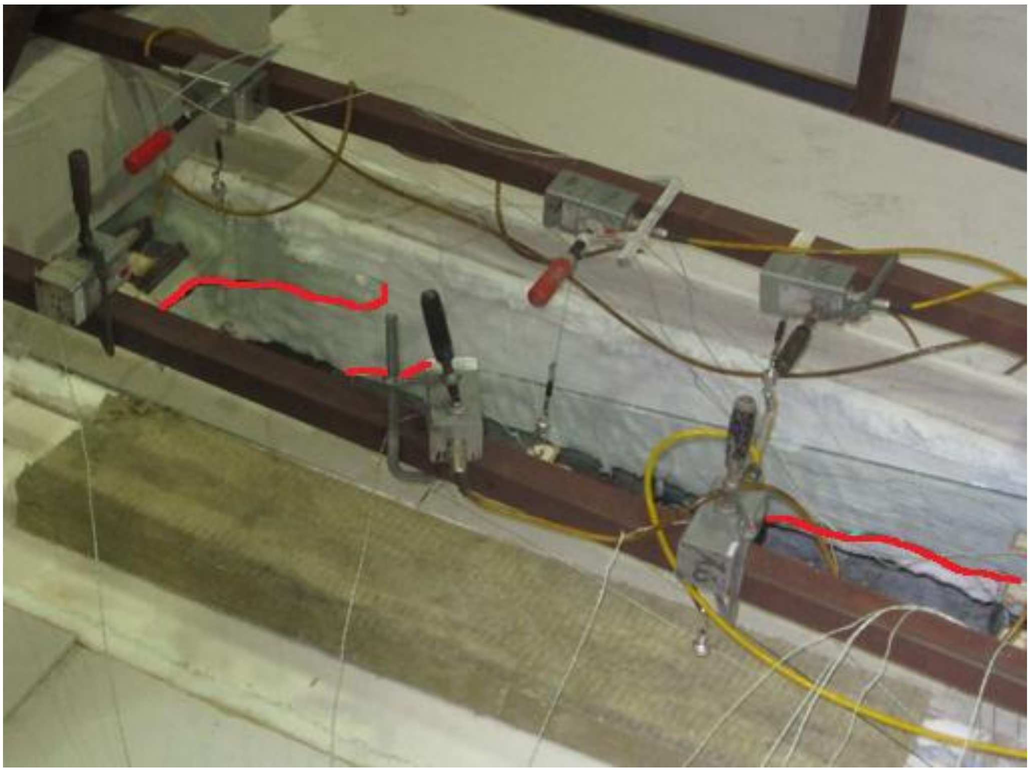


Figure 5.35 Break pattern pane B

Glass Temperature

The following graph illustrates the temperature data of installed thermocouples. The thermocouples number fourteen and fifteen (tk14&15) recorded the highest temperatures during this test. The maximum temperature on the glass surface was around 100°C.

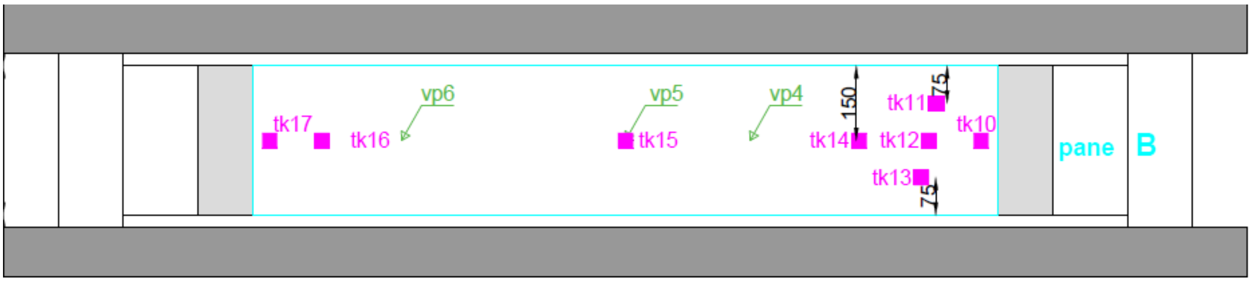
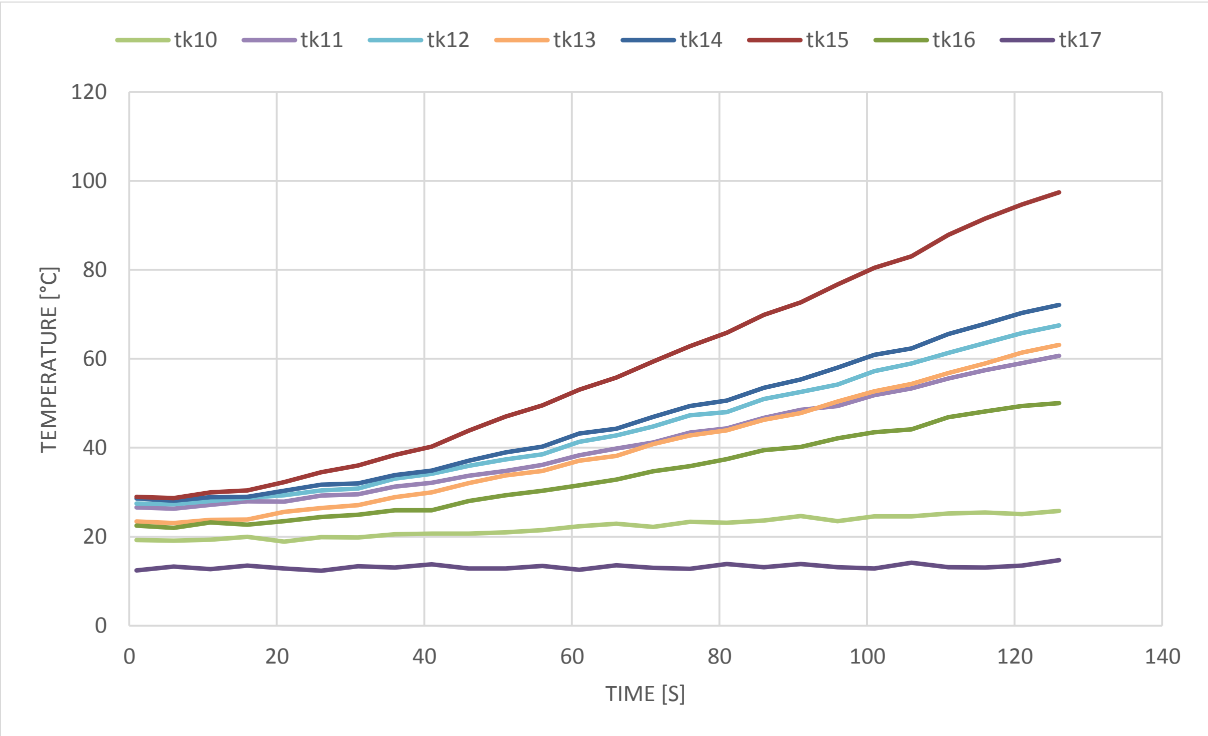


Figure 5.36 Top view pane B



Graph. 5.3 Pane B temperature

5.3.5 Results Discussion and Conclusion

End parts of panes A& B are both located at steel supports. The place of these supports is at masonry part of the furnace, which means the glass area on top of this support (blue area) got lower temperature than rod ones. Because the blue area is not in direct contact with furnace temperature. Graph 5.3 shows there is temperature difference around 70°C on the glass surface. The fracture for both pane A & B are occurred close to boundary line (green line) between this two areas. This means a thermal break occurred at both panes.

Moreover the supports are made in steel. The behavior of steel during fire is not same as glass. That is why this supports had different temperatures (lower). This steel support with their lower temperatures were in touch with glass which had higher temperature. This temperatures difference resulted also a thermal break around supports.

Maximum temperatures were 45 and 100 °C for pane A and B respectively. Both recorded temperature are not high. It means that thermal break is more dependent on the temperature difference and can also occurs at low temperatures.

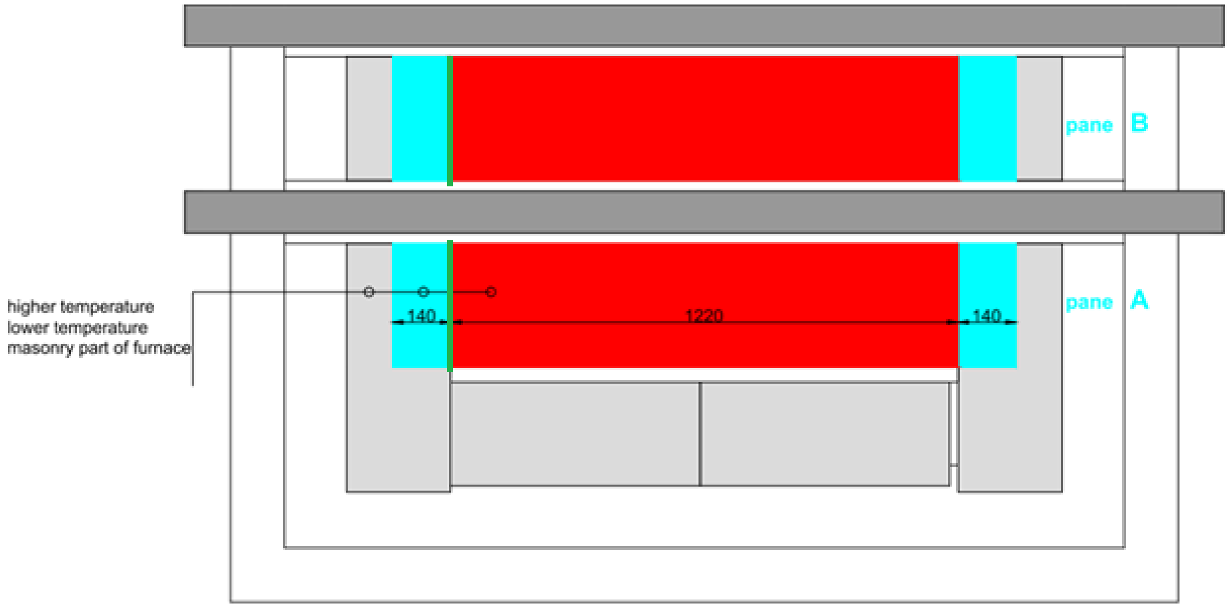


Figure 5.37 location of warm and cold areas

As it mentioned before the furnace needs at least 5 minutes in order to have an uniform heating. Test series 1 took around 2 minutes. This means both panes A and B were heated by non-uniform heating. This seems to imply that this non-uniform heating had also influence on the glass break. "Glass can also break as result of stress produced by non-uniform heating. The resulting fractures tend to curve randomly about the pane (as opposed to, which are almost always straight lines). Glass expands when heated, so convected or radiant heat raises the temperature of the exposed portion of the glass pane, and it expands. The portion of the pane behind (or in) the frame or modeling is protected or shadowed and "sees" no heat, and because of its poor thermal conductivity, maintains its starting temperature and size. Tensile stress build up until the tensile strength of the glass is exceeded. Studies of this process have shown that it is dependent on the strength and type of glass;

ordinary window glass breaks when there is a temperature differences about 70 °C" (John D. DeHaaan 1983)

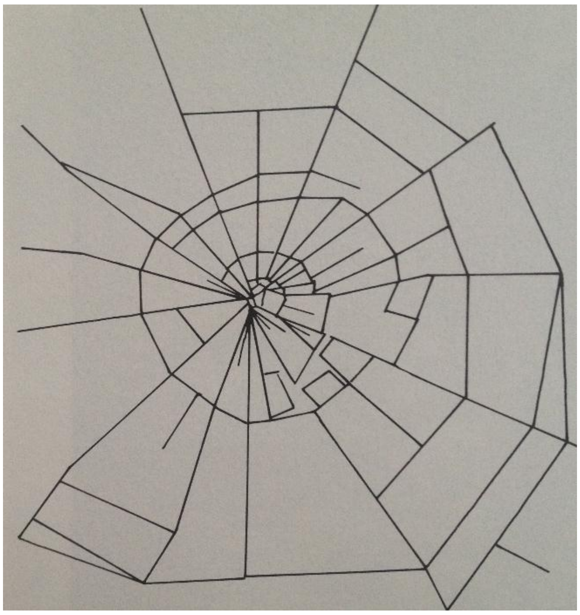


Figure 5.38 Typical mechanical fracture

Figure 5.39 Curve break line

$\sigma = E\,\varepsilon = E\,\alpha\,dt = 72 \times 10^{9} \times 8.3 \times 10^{-6} \times 70 = 41.83$ *[Mpa]*

41.83 [MPa} is close to maximum theoretical stress for annealed glass which is 45 MPa

Where:

σ = *stress due to temperature expansion [N/mm^2, MPa]*

E =Young's Modulus= 72 X 10^9 [N/mm^2]

ε = strain

α = temperature expansion coefficient = 8.3 X 10^{-6} [mm/mm°C]

dt = temperature difference=70 [°C]

Pane A is broken 85 seconds earlier than pane B, because this pane carried 16 kg more than pane B. This extra load increased the moment. The section modules did not change. Higher moment value resulted in higher stress in the pane. That is why pane A failed earlier.

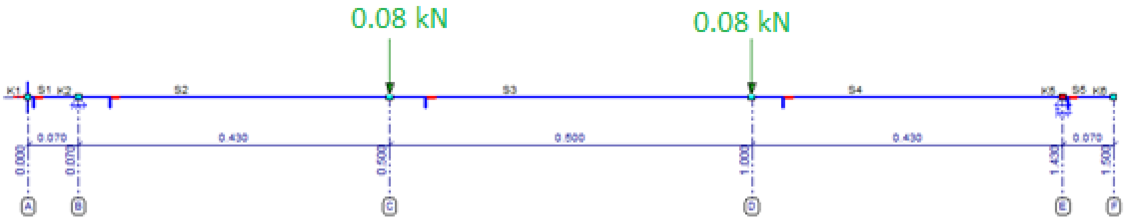


Figure 5.40 Mechanical diagram pane A

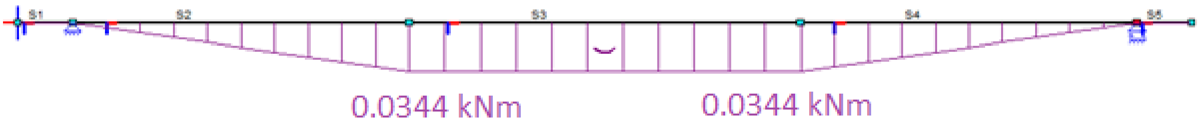


Figure 5.41 Moment line

$$\sigma = \frac{M}{W} = \frac{34400}{5000} = 6.88\ [MPa]$$

$$\sigma = 41.83 + 6.88 = 48.71\ [Mpa]$$

$q \uparrow \Rightarrow \ M \uparrow \ \Rightarrow \ \sigma \uparrow$ *(Pane A & B had same geometry⇒ W constant)*

The hand calculations show that 16 kg resulted in stress of 6.88 MPa. Most of the stress came from non-uniform heating which is around 42 MPa. This vertical load (16 kg) is only 9% of load that pane B carried without any break at room temperature.

Figure 5.42 Glass pane with 84 kg vertical load at room temperature

The following pictures show how 84 kg were placed on the pane in six steps.

Figure 5.43 Six steps

The section modules increased, when the pane is twisted 90º . This growth will decrease the amount of stress in the pane. It should be mentioned that TUDelft performed some bending tests for lying and standing annealed glass beams at room temperature in 2009. The sizes of the beams were 1000 m long, 100 mm wide and 10 mm thick. These test results show that lying glass resisted longer than standing glass. It is interesting to know if this changing at high temperature will give the same results as the testing at room temperature. In order to answer this question, two panes are tested vertically during next test series

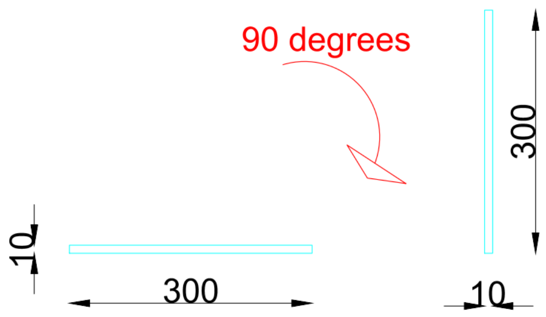


Figure 5.44 Testing pane vertically

Glass type& orientating	Average failure stress [Mpa]
Annealed lying	42
Annealed standing	27

Table. 5.3 TUDelft results (source The strength of annealed, by F. Veer, C. Louter, F. P. Bos)

5.4 Experiment Series 2

5.4.1 Test Setup

Two annealed glass panes (D & E) were tested vertically during this series. Pane D is heated from 3 sides. Pane E is heated only form bottom side. Following paragraph describes this setup in more details.

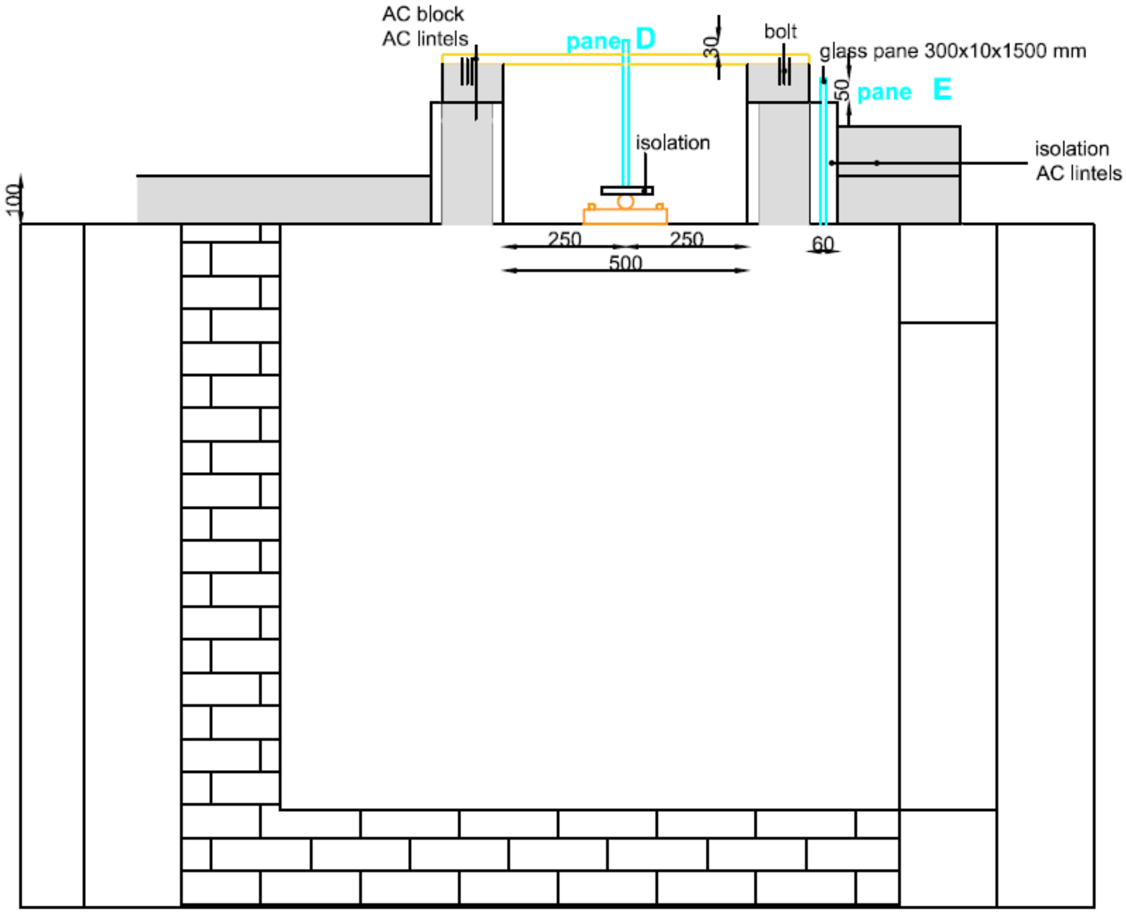


Figure 5.45 Cross section setup test serie2

First of all the glass pane D is placed vertically on the steel supports. This pane is located between two autoclaved aerated concrete (AAC) lintels. The distance between middle of pane and ACC lintels was 250 mm. In this way furnace temperature had enough space for heating three sides of pane D.

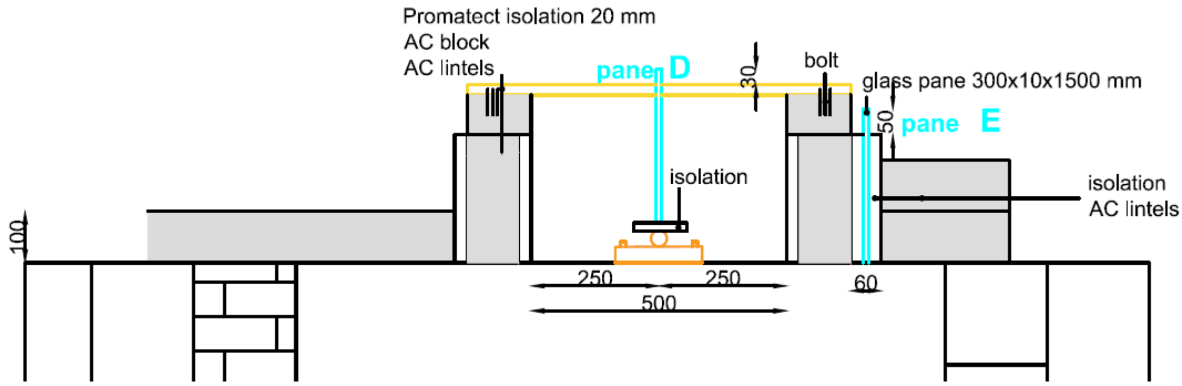


Figure 5.46 locations of panes D and E

Figure 5.47 Placing pane D vertically

Test series 1 showed that the connection between steel and glass is a critical point for glass failure. Because steel and glass temperature are not same. Piece of isolation material is used between glass and steel, in order to limit the temperature difference between these two materials.

Figure 5.48 Isolation between glass and steel support

Afterwards two Promatect isolation are placed left side and right side of the pane D. These isolation layers are fixed in the ACC blocks by using a number of bolts. The empty spaces are filled with isolations. 30 mm of glass is not covered with Promatect, in order to have some spaces to install thermocouples.

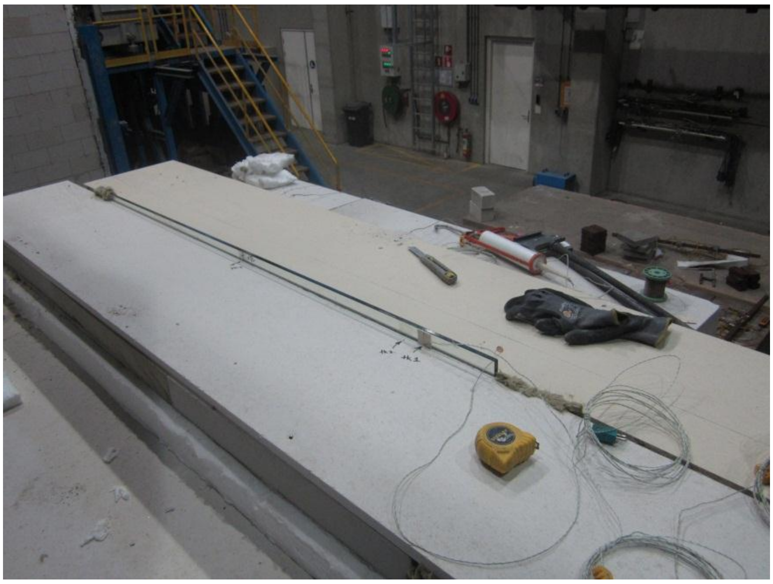


Figure 5.49 location of pane D between two promatect isolation layers

The following figure shows the bottom side of pane D. It is obvious that three sides of this panes are heated by hot air during the test.

Figure 5.50 Bottom side pane D

Afterwards pane E is placed between two isolation layers. The pane is heated only form bottom side in this way. But 50 mm of the pane is not covered with isolation in order to reserve some spaces to install thermocouples. It should be mentioned that no steel supports are used for this pane. It was not possible to place a support or the pane would become unstable.

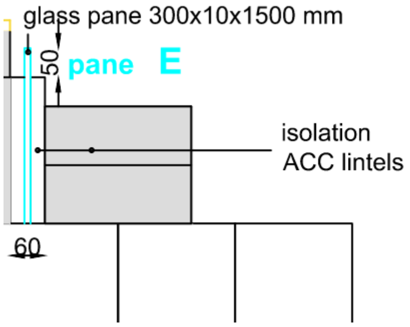


Figure 5.51 Test setup for pane E

Figure 5.52 location of pane E between ACC beam and blocks

Furthermore the thermocouples are installed on both panes.

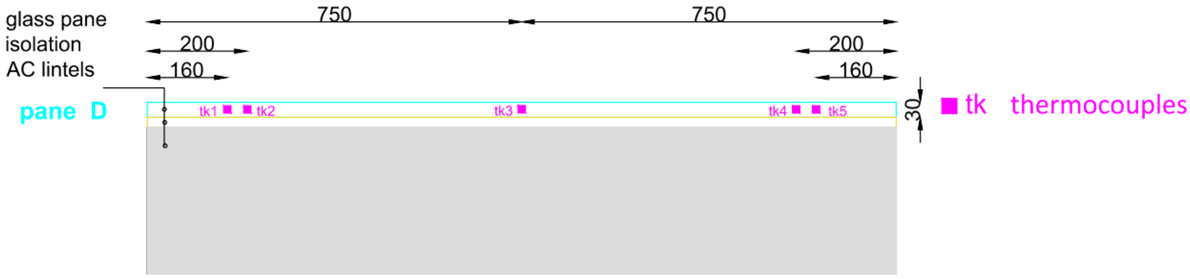
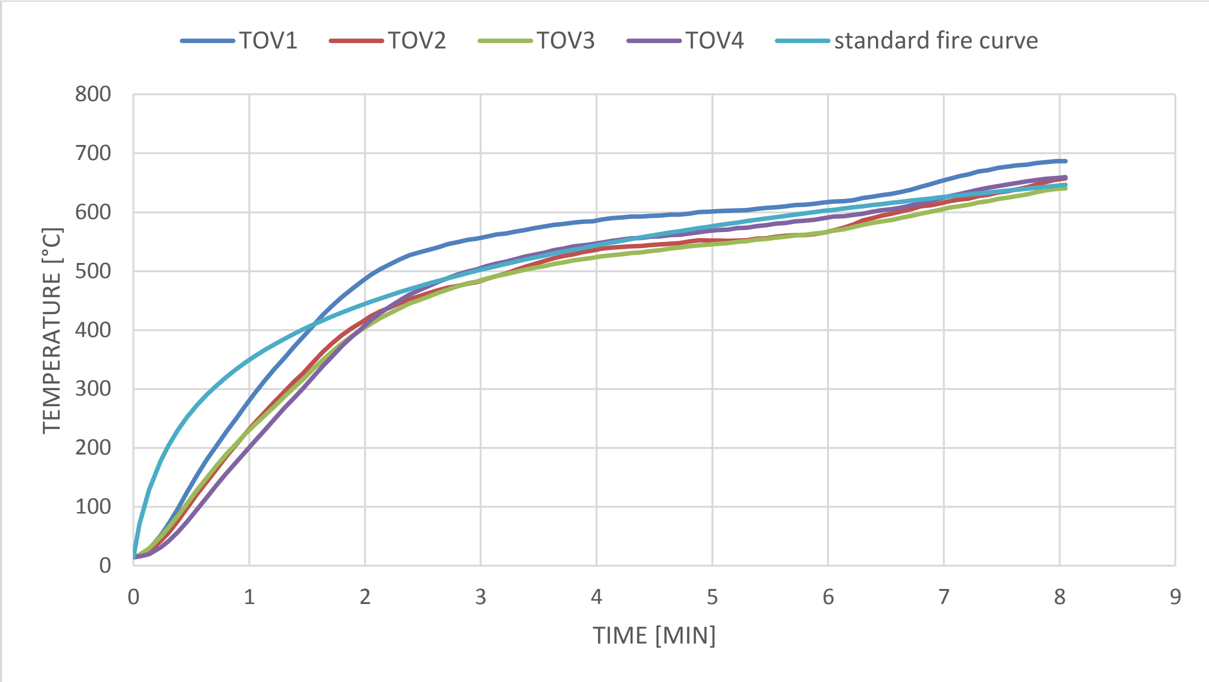


Figure 5.53 Installed thermocouples on pane E

Figure 5.54 Front side pane E

5.4.2 Furnace Temperature

Four plate thermometers are used to measure the temperatures at different locations inside the furnace. The following graph present these measurements. This graph shows that the furnace reached almost the temperature of standard fire curve after 5-6 minutes



Graph. 5.4 Furnace temperature

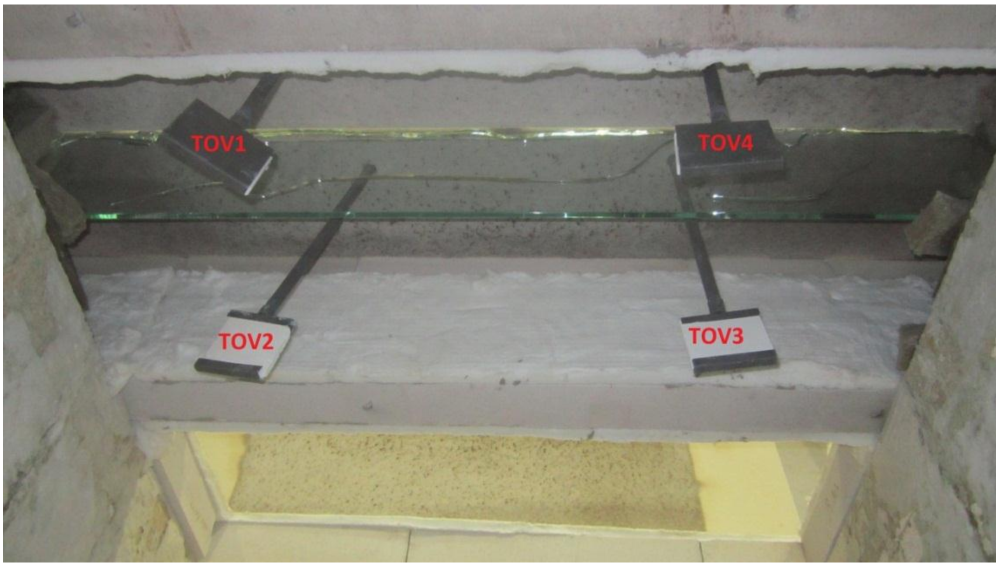


Figure 5.55 Bottom glass pane D view with location of installed plates thermometers

Figure 5.56 Top glass pane D view with location of installed plates thermometers

5.4.3 Pane D

Fracture

Pane D is broken after 88 seconds nearby the end of glass pane and steel supports. The following figure shows that the fracture started close to the place of tk4, which is close to the end part of pane. The moment for this fracture is recorded. Please watch video “test3 annealed vertical” at moment 9:34.

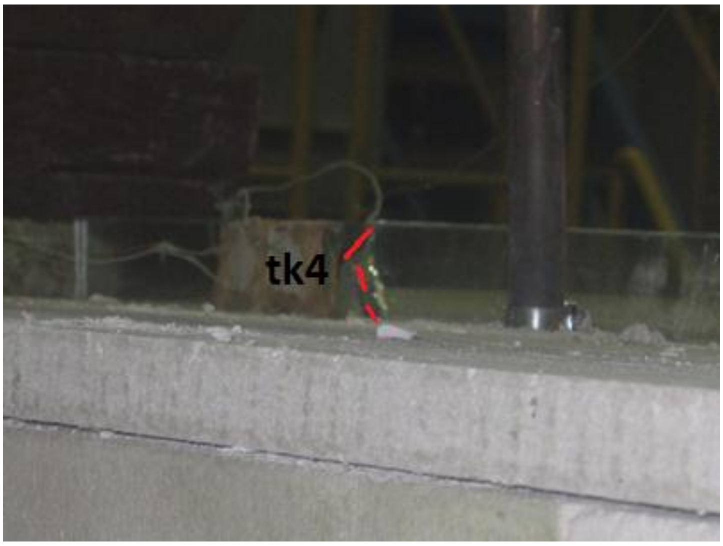


Figure 5.57 location of pane D fracture

Figure 5.58 location of pane D fracture

Figure 5.59 Pane D after break

Glass Temperature

The following graph illustrates the temperature data of 5 thermocouples. Which are installed on the glass surface. It should be mentioned that the area of the glass whose temperature is measured is one that was not in direct contact with furnace temperature. Thermocouples two and four (tk2&4) recorded the highest temperatures during this test. The maximum temperature on the glass surface was around 60 °C after 88 seconds.

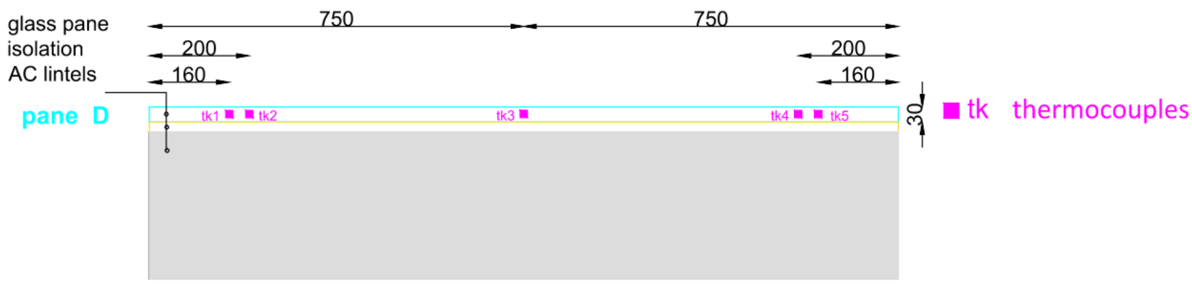
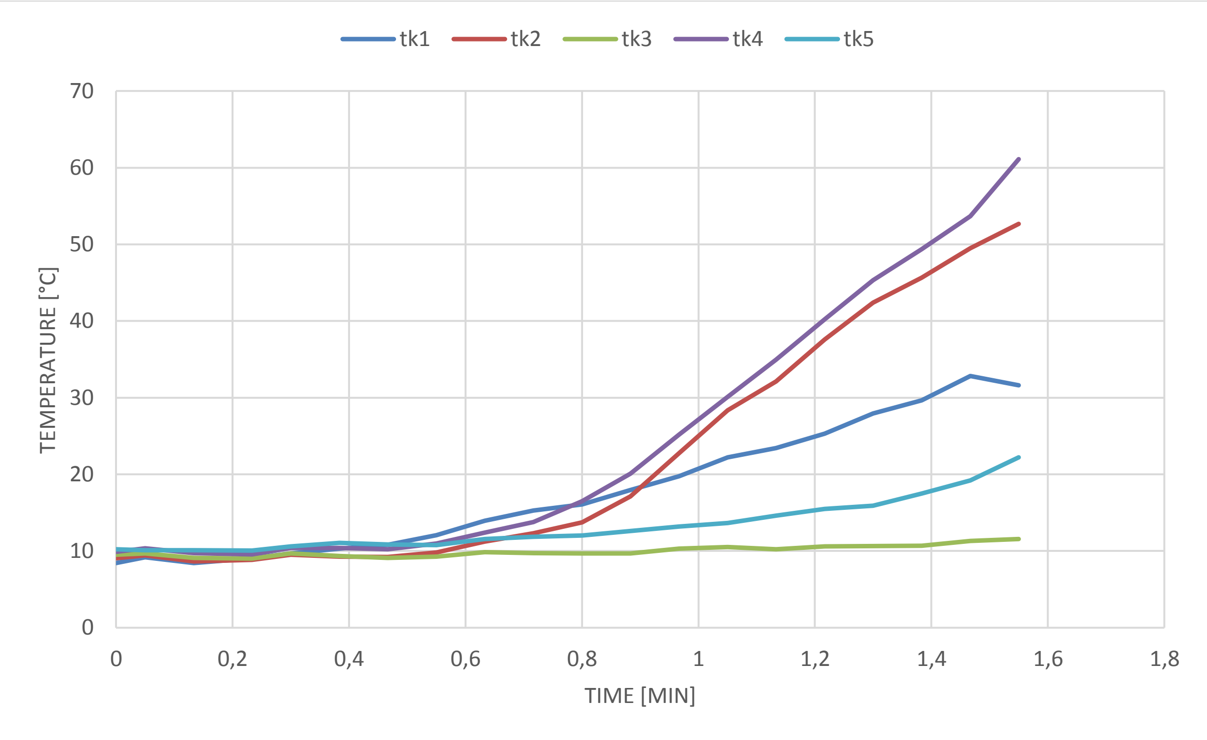


Figure 5.60 location of 5 thermocouples on pane D



Graph. 5.5 Glass (pane D) temperature

Deflection

The deflection in the middle of the pane is measured. The bending of the pane was less than 1 mm due to the fact that it was placed vertically.

5.4.4 Pane E

Fracture

This pane is broken after 437 seconds close to left and right steel supports.

Figure 5.61 Pane E before break

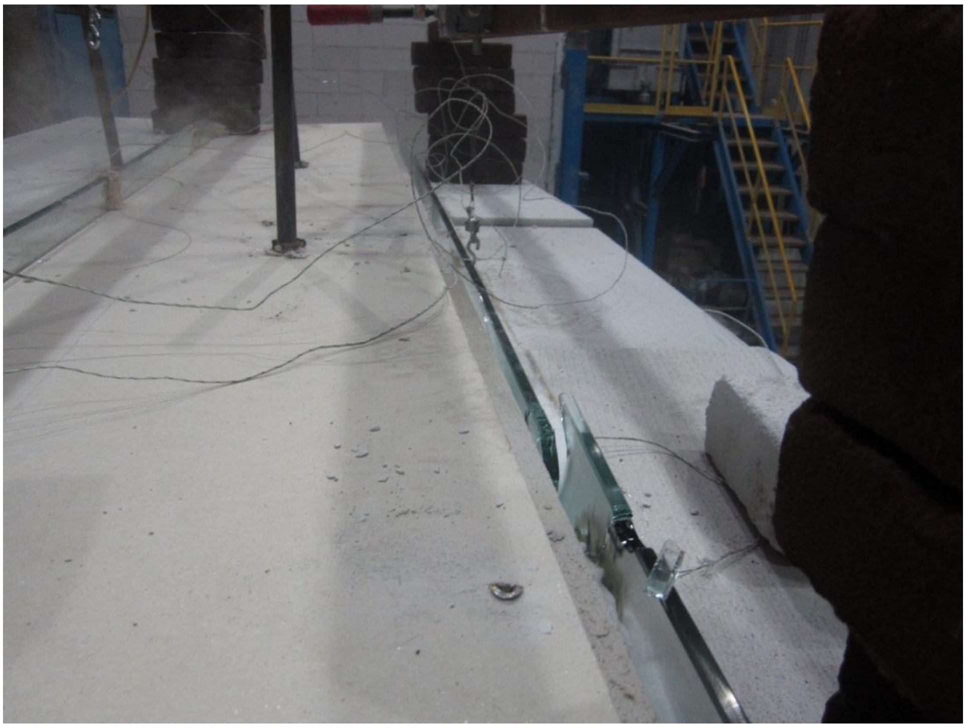


Figure 5.62 Pane E after break

Glass Temperature

The following graph shows the temperature of glass area that was not in direct contact with furnace temperature. Pane E is heated only from the bottom side, which was a small area, because the thickness of the glass is only 10 mm. The result shows that the temperature at this area remains almost constant.

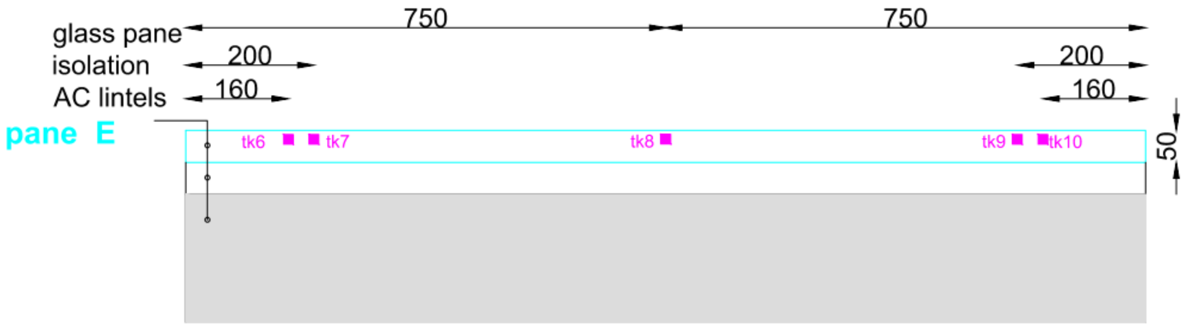
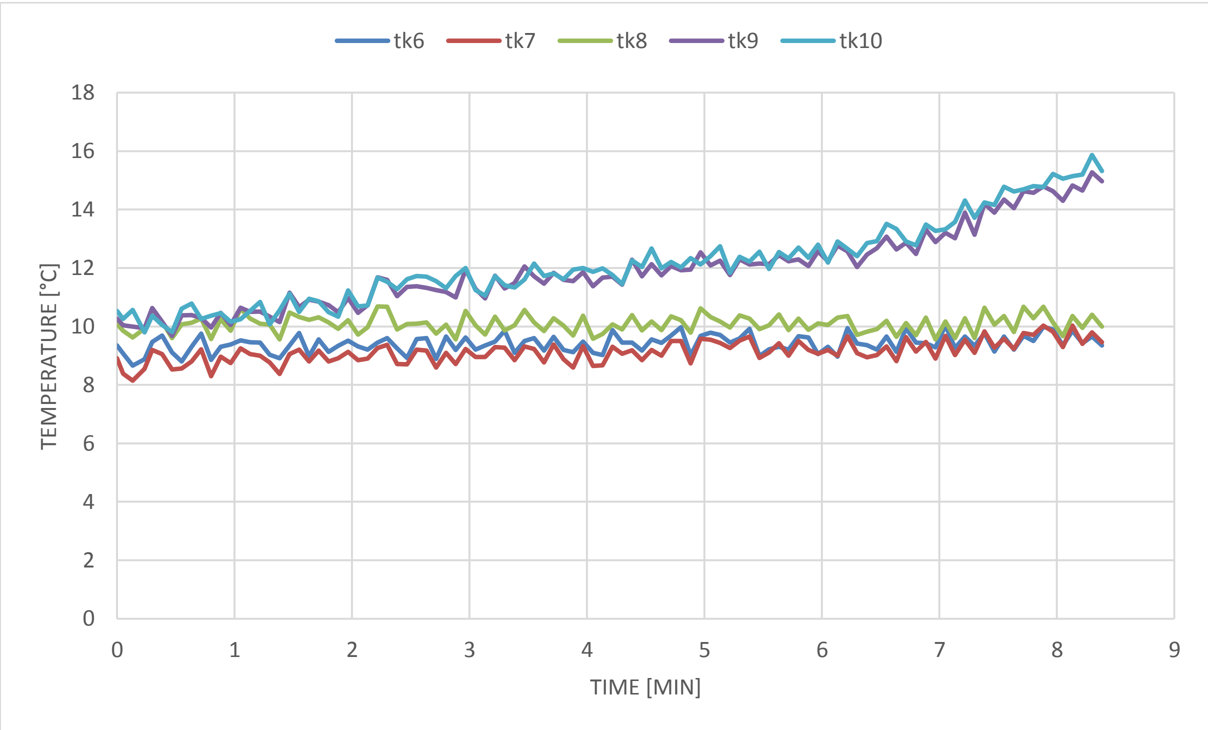


Figure 5.63 Location of 5 thermocouples on pane E



Graph. 5.6 Glass (pane E) temperature

Deflection

The deflection in the middle of the pane is measured. The bending of the pane was less than 1 mm due to the fact it was placed vertically.

5.4.5 Results Discussion and Conclusion

Testing results of pane D and E show that using annealed glass vertically does not help the annealed glass to resist against high temperature. Pane D is broken after 88 seconds which is 43 seconds earlier than pane B (tested horizontally). This is not consistent with expectations that are explained in the conclusions of pervious test. As it is mentioned before panes from two different manufacturers are used during test1 and 2:

- pane D and E produced by AGC
- pane A and B produced by Zoetermeerse Glashandel B.V.

Pane E is heated only by its bottom side. This heated area is very small compared to the rest of glass area. Because of this hot air more time is needed to heat all sides of glass. For this reason is annealed glass is stayed longer (more than seven minutes) without any break.

The following figure shows the place where the break line started (green line) in panes D and E. Both fractures are occurred around the end part of glass panes. These parts were areas in the glass which were not in direct contact with furnace temperature. That is why their temperature was lower than the temperature in the middle of the glass. Moreover the steel supports are located under this part of the glass. The behavior of steel was not the same as the glass during fire. The steel and glass had different temperature during the test. As it was mentioned before, some glass areas were only in contact with room temperature. This part of glass is shown above the orange line in the following figure. Therefore, this area had lower temperature than area below the orange line. For all these reasons, the end parts of the glass became critical. Glass is broken due to temperature difference in these parts.

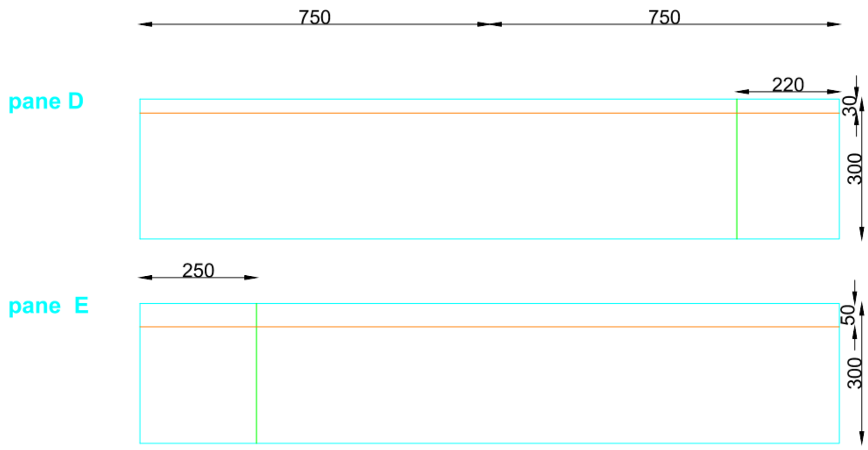


Figure 5.64 Critical locations

Temperature difference caused a thermal break for both panes D and E. This phenomenon also happened during testing pane A and B. It means that this is a weak point of annealed glass and need to be prevented for the following experiment series.

One of the observations during tests1 and 2 was that some parts of the glass got lower temperature, because these parts were not in direct contact with fire. The glass panes are placed in the furnace for the next experiment series. In this way all side of the panes got almost the same amount of heat. And it was possible to check if this can be helpful for annealed glass.

Testing in the same furnace was difficult and required extra preparing works:

- glass panes did not fit in the furnace and needed to be shorter
- front side of the furnace needed to be closed with brickwork, in order to save space for placing the furnace camera

For these reasons, another Efectis furnace (bigger one) is used for the next test series. The description of this furnace is written under paragraph equipment.

5.5 Experiment Series 3

5.5.1 Test Setup

The annealed panes J & K (AGC products) are used for test series3. This series were conducted in the bigger furnace, which was 4.0x2.0 meter. Self-weight was only the load for both panes. Upside of pane K is covered with isolation material in order to create a situation like the previous tests (pane B; glass is heated by three sides). In this way, it was possible to check if the previous observations were correct. However, pane J was without any covering and was heated on all four sides.

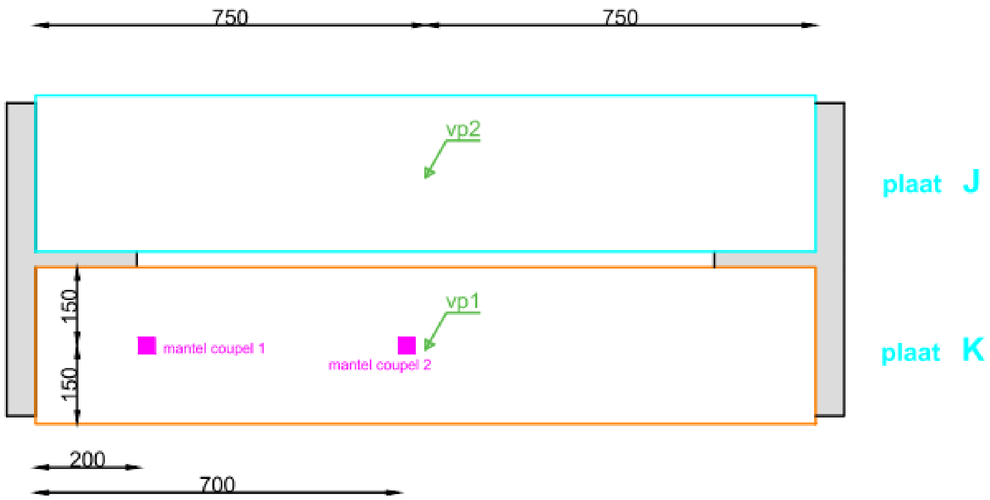


Figure 5.65 Top view test3 setup

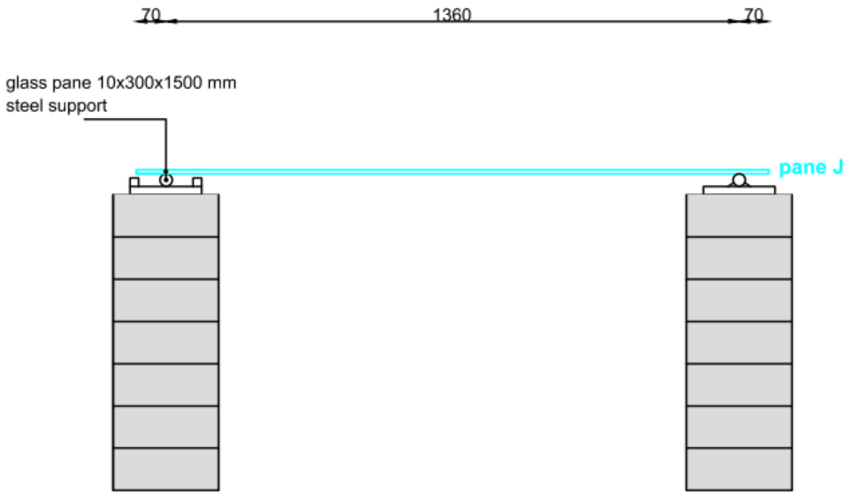


Figure 5.66 Cross section pane J

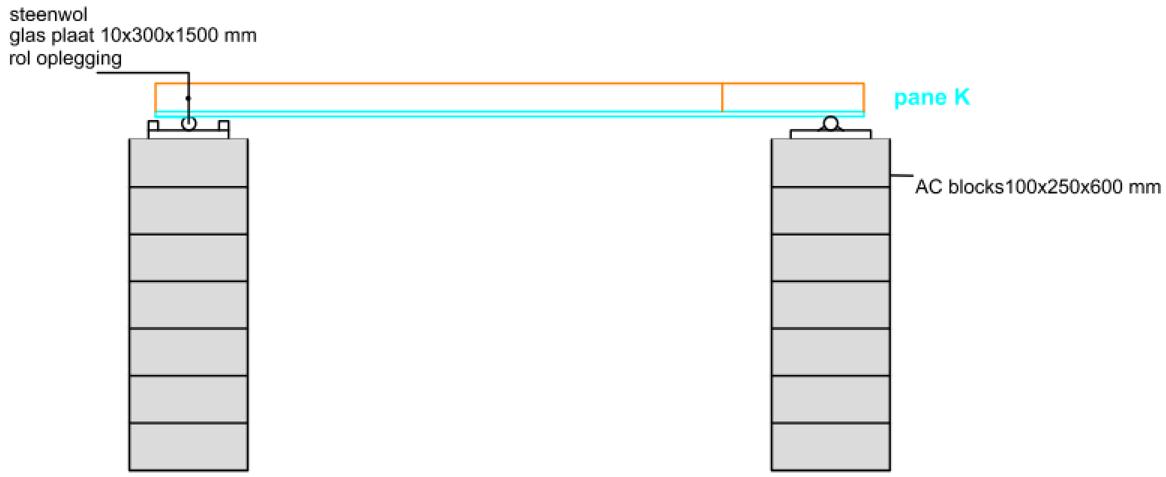


Figure 5.67 Cross section pane K

Firstly, ACC blocks are placed in the middle of the furnace. Then glass panes with steel supports are put on top of these blocks. Afterwards Mantel couples and deflections measurer are glued on the glass surface. Moreover, an isolation layer is placed on top of the pane K. In the end five furnace thermocouples are placed at various places around the specimens.

Figure 5.68 location of ACC inside the furnace

Figure 5.69 Pane J and K inside the furnace

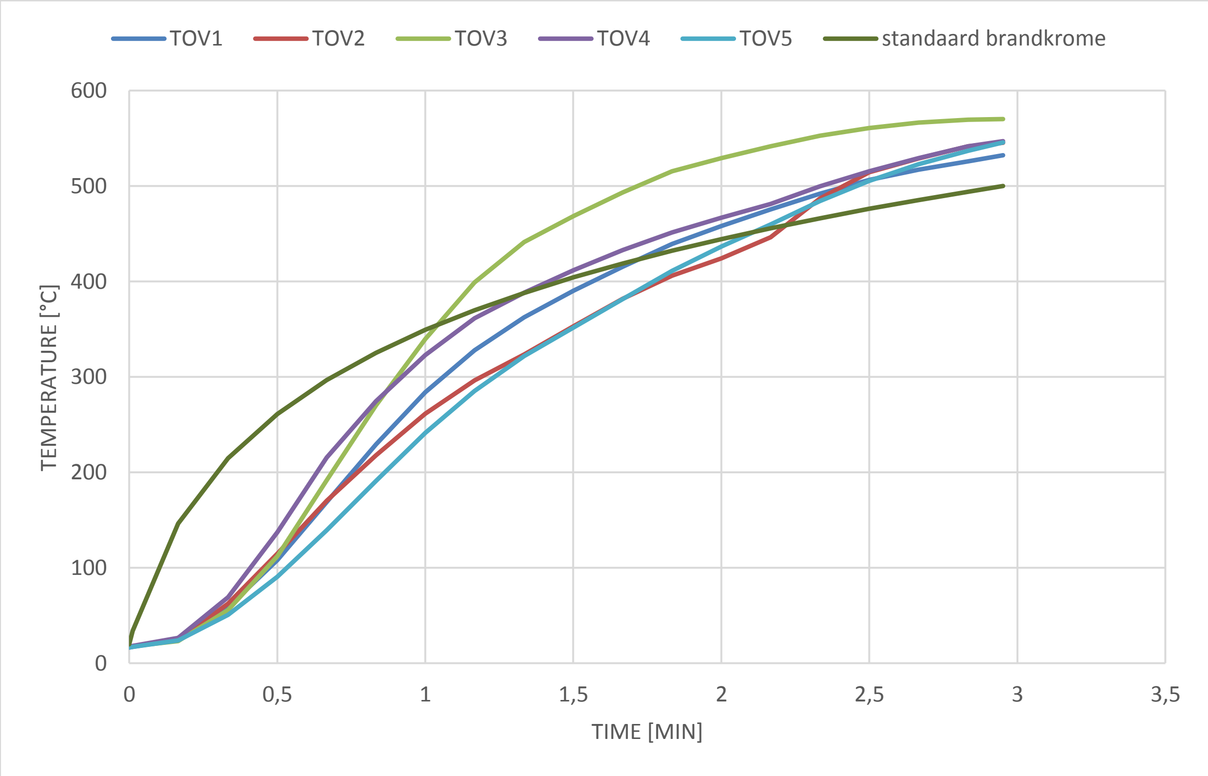
A Furnace camera is used for recording this test. This camera is placed at the roof of the furnace, to record the top view of glass panes during the test.

Figure 5.70 Oven camera and deflection measurer

Figure 5.71 View oven camera form inside the furnace

5.5.2 Furnace Temperature

The graph illustrates the furnace temperature at four different places.



Graph. 5.7 Furnace temperature

Figure 5.72 location of plates thermometers

5.5.3 Pane J

Fracture

Pane J is broken after 63 seconds close to the left steel support due thermal break. The reason for this thermal break is temperature difference between steel and glass as it is explained in the previous paragraphs. Furthermore this phenomenon has occurred 48 seconds earlier than in pane B. The only explanation for this is that Zoetemeer glass (pane B) had better treatment (poly slijpen) during manufacturing process than AGC glass (pane J). This difference has also occurred between test1 and 2.

Pane J did not fall down after this thermal break. This pane is broken after 126 seconds in the middle. This means that even if no thermal break occurs for annealed glass, this glass type (without any extra requirements) is still very weak to be used as a structural material. And these glass type must not be used as structural element.

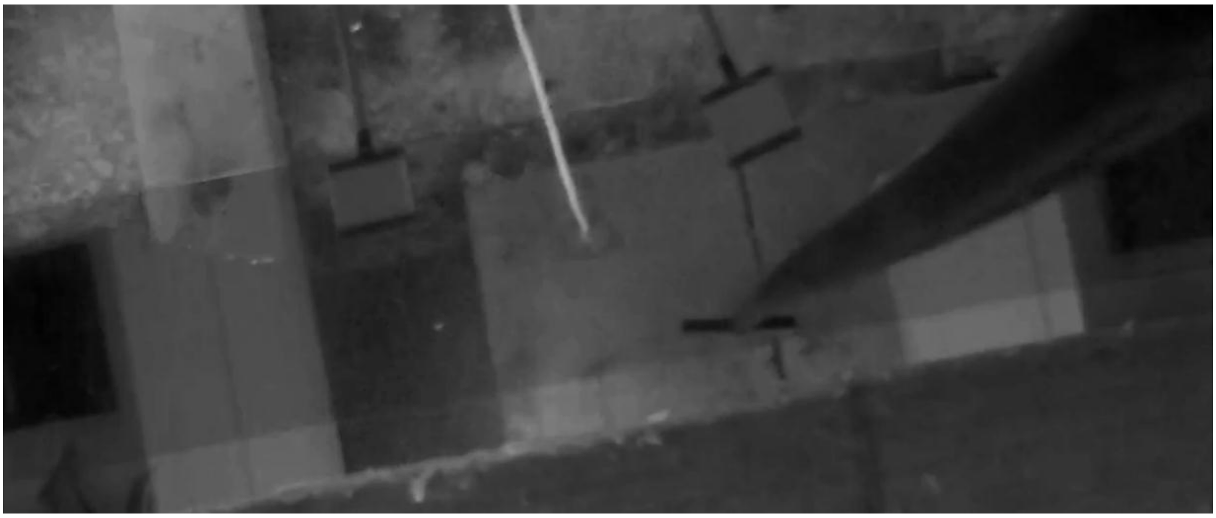


Figure 5.73 Pane J before break

Figure 5.74 Pane J after 63 seconds

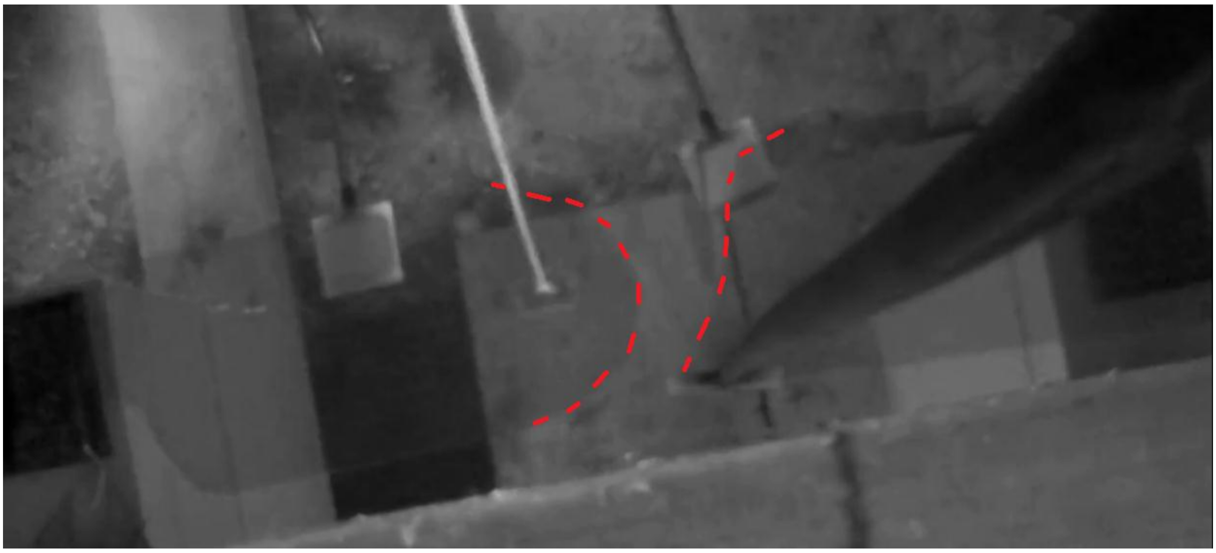


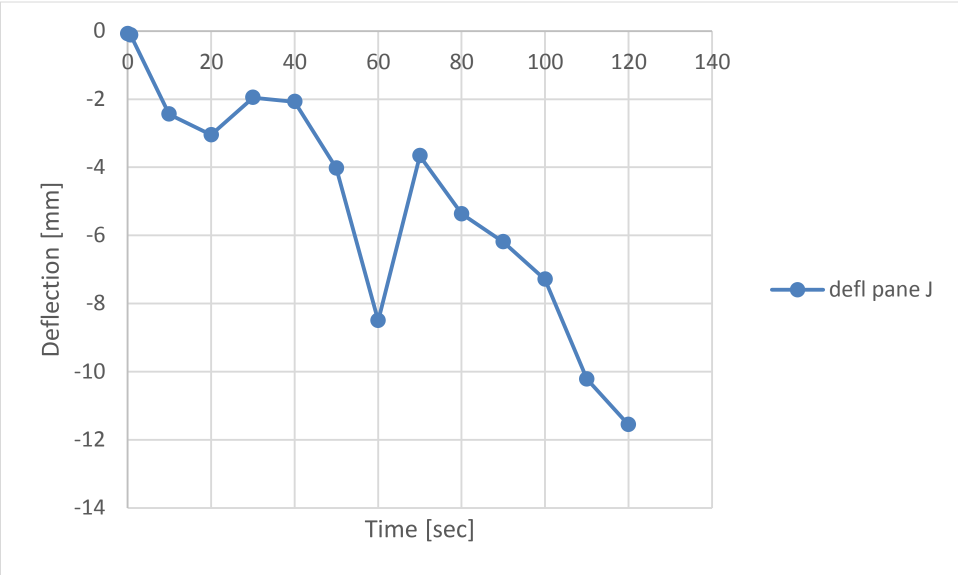
Figure 5.75 Pane J broke in the middle after 126 seconds

Glass Temperature

Unfortunately it was not possible to measure surface temperature of pane J. That is why no data is available.

Deflection

The following graph illustrates deflection of pane J during this test. Deflection result value should be positive if pane bends downward. As can been seen in graph, all values are negative. It might sound surprising, however these values do not present deflection of glass. Deflection is measured using special wires. These wires were in direct contact with flames. Therefore all wires are heated and afterwards are extended. That is why negative values are recorded during measuring. And this does not mean that the glass is deflected upwards. Results shows that the glass did not bend during this process. This test took only two minutes and the glass is not heated enough for bending. The results show that these wires are extended considerably during the performed tests. This means that measured glass deflections are not exact and reliable. This method is discussed in the chapter "Discussion" in more details.



Graph. 5.8 Deflection results pane J

Figure 5.76 Used wire for deflection measurements

5.5.4 Pane K

Fracture

Pane K is broken after 47 seconds close to left and right steel supports. The location of thermal break is exactly the same as pane J. However this occurred 16 seconds earlier, because the temperature difference is higher between top side and bottom side of glass due to using isolation material.

Figure 5.77 Pane K after 5 seconds

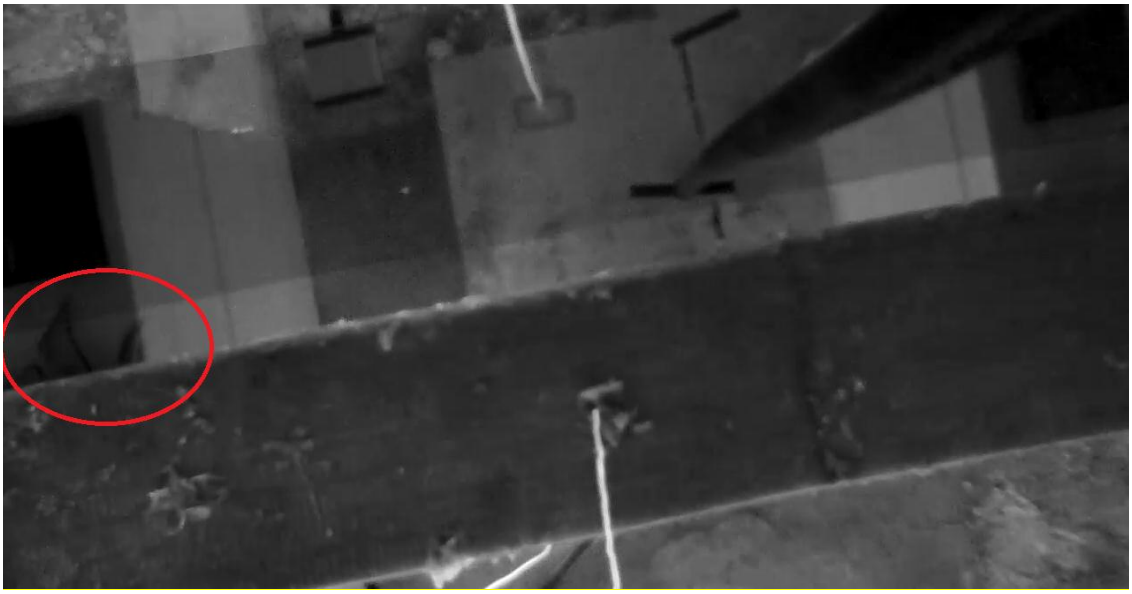


Figure 5.78 Pane K after 47 seconds

The following figures show right and left sides of pane K after its break. As can be seen in these figures two symmetric break lines occurred at both sides, because the big furnace heated panes from left and right with two symmetric flames. However, the small furnace (used furnace during test1 &2) heated panes only form one side. That is why breaking lines were not symmetric during test1 and test 2.

Figure 5.79 left side pane K after break

Figure 5.80 Right side pane K after break

Glass Temperature

Usual thermocouples cannot be used as measuring middle in furnace. Because of this mantel couples are installed on the top side of pane K. The following graph illustrates temperature of these two mantel couples.

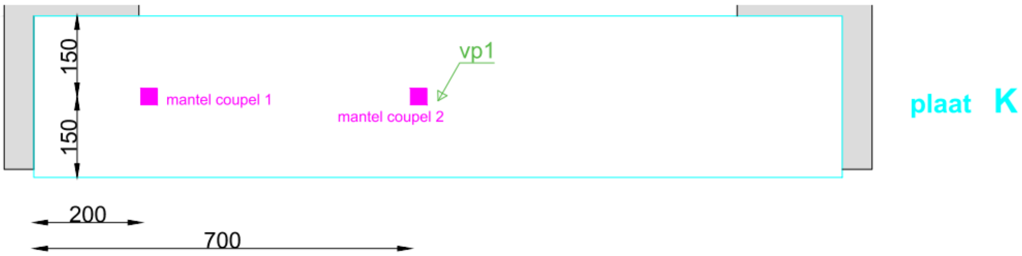
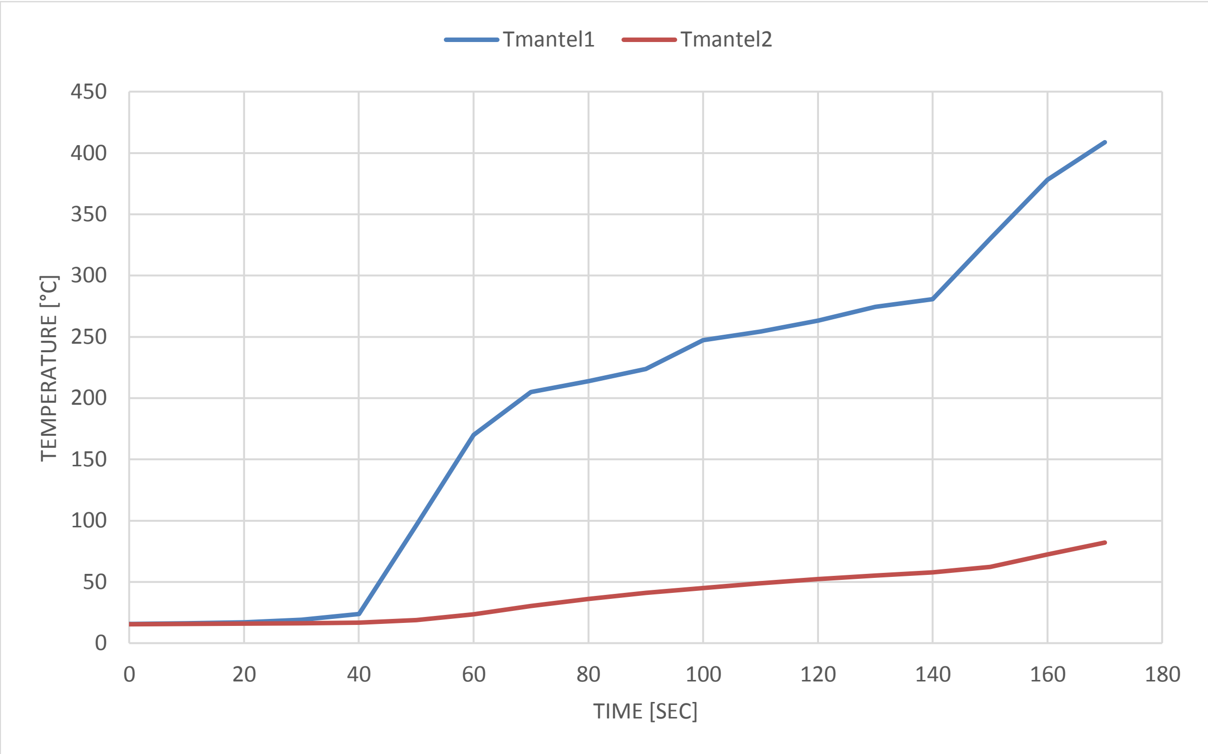


Figure 5.81 Top view pane K



Graph. 5.9 Glass (pane K) temperature

Pane K is broken after 47 seconds close to place of mantel couples1. As can be seen in the graph, temperature of this couple increased sharply after this moment (47 seconds), because pane K moved after break. Therefore mantel couple1 lost its connection with glass. The following figure (pane K after break) shows that mantel couple1 was not pasted anymore on the glass and it did not measure glass surface temperature after 47 seconds. But mantel couples2 kept its connection. In other words mantel couples2 shows correct glass temperature during this test.

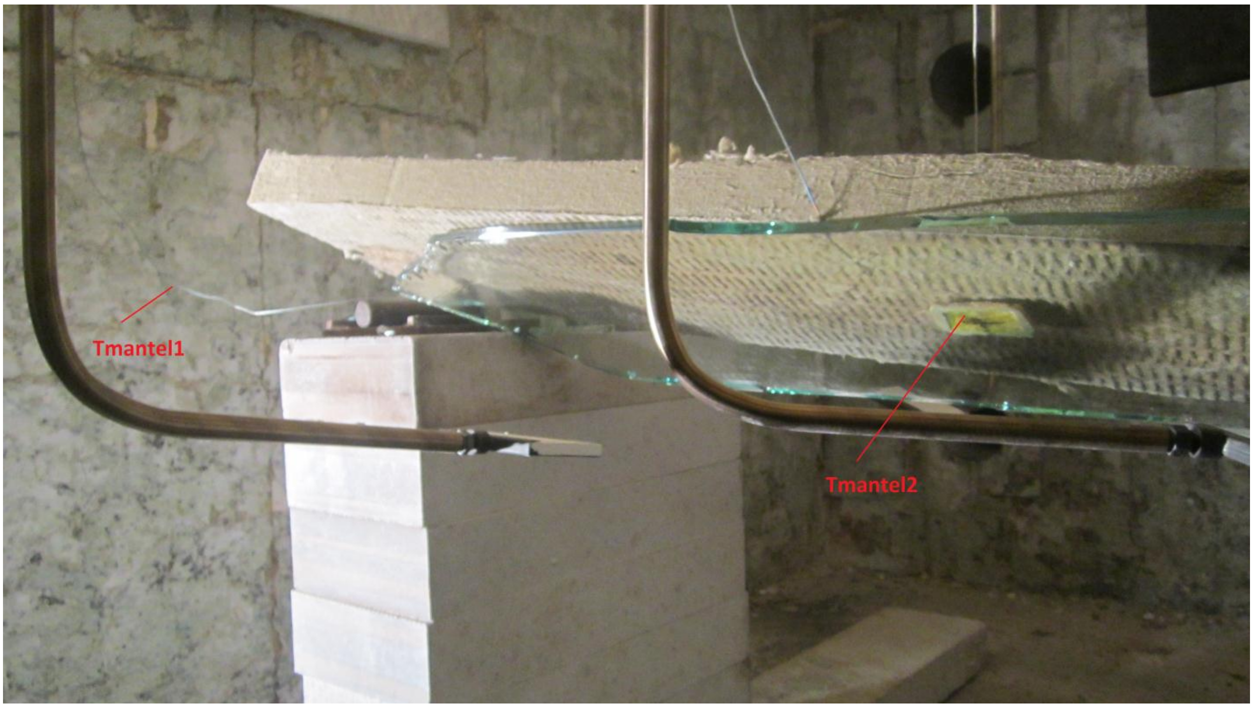
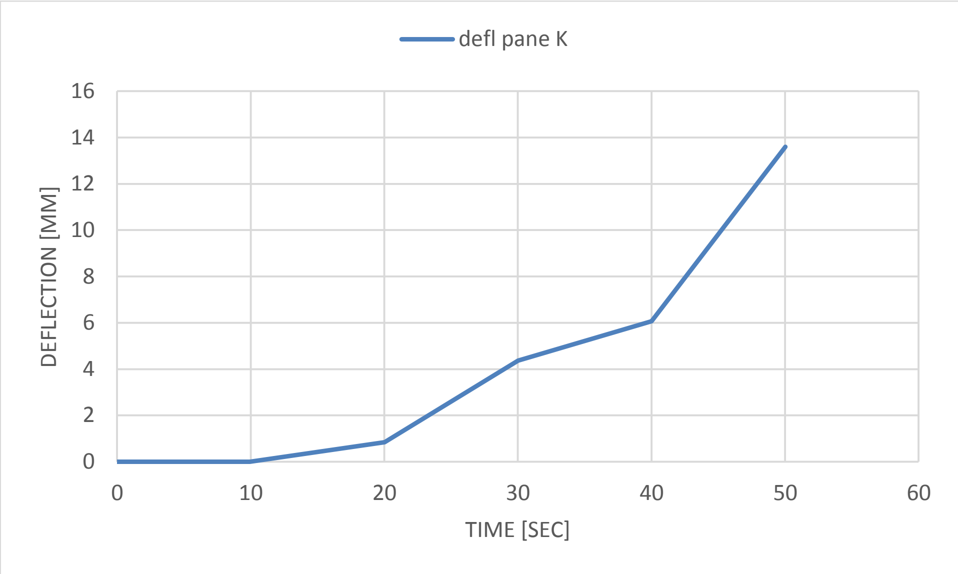


Figure 5.82 Used mantelcoples for temperature measuring

Mantel couples results show that temperature top side of pane K was around 23 °C (during break) which is low. This low temperature cannot be a reason for this break. Temperature difference between glass and steel plays a major role in glass failure. Using isolation material also make an extra temperature difference between top and bottom sides of the glass. That is why thermal break for pane K occurred earlier than for pane J.

Deflection

The following pictures show the deflection of pane K in the middle of pane. Result values are positive which means glass is bended downwards. Pane K is covered with isolation material. Because of this covering top side of glass has lower temperature than bottom side. That is why the glass is bended toward the bottom side (warmer side) and positive values are recorded. Furthermore wires are also covered with this isolation material. Therefore, the wire is heated less than the previous test. Results shows that temperature difference accelerates glass deflection and this should be prevented.



Graph. 5.10 Glass (pane K) Deflection results

5.5.5 Results Discussion and Conclusion

Annealed pane J and K are tested during this experiment. Results of this test and pervious tests show that thermal break occurred during all tests. Thermal break is the result of temperature difference in glass. Two reasons are considered for these temperature differences; all parts of the glass are not heated equally. For example ends parts of panes A and B were colder than the middle part. Moreover the connection between glass and other material (steel supports) is a weak point and was another reason for this thermal break.

Temperature difference increased stresses in panes. Annealed glass cannot resist this rise because this glass type has limited strength capacity. That is why all tested pans are broken very quickly. Annealed glass can be used as structural material if glass strength is increased from current level. Otherwise this glass is still sensitive to temperature differences and unequal deformations. And annealed glass must not be used as structural element under temperature load.

5.6 Experiment Series 4

5.6.1 Test Setup

Two fully tempered glass (panes N and O) are tested during this series. Pane N carried only it's self-weight. But Pane O also carried 16 kg. Bricks are applied as vertical loads on top side of panes. Furthermore no isolation material is used as a cover on glass surface. In this way, both panes are heated from four sides.

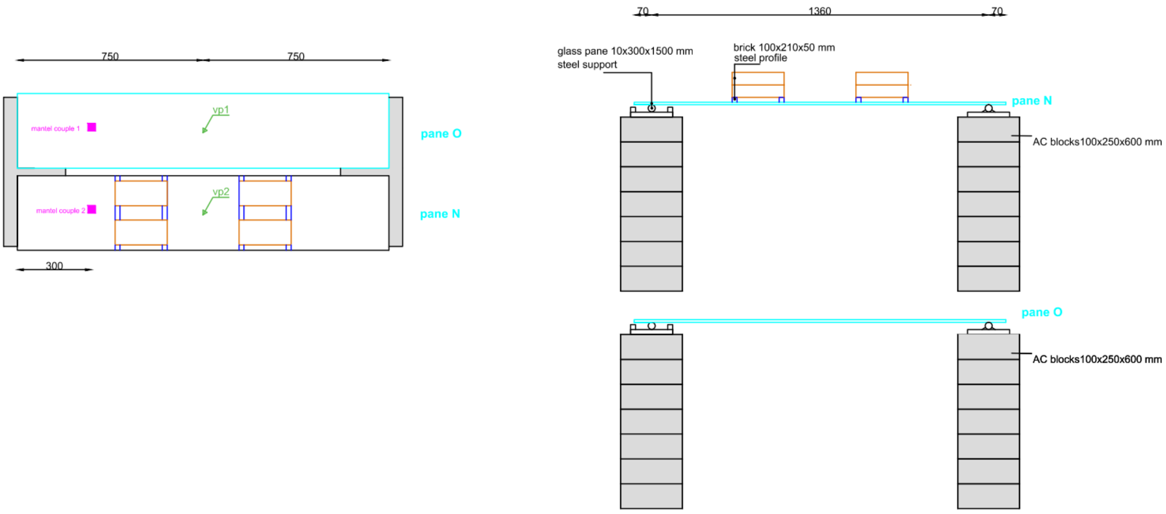


Figure 5.83 Test4 setup

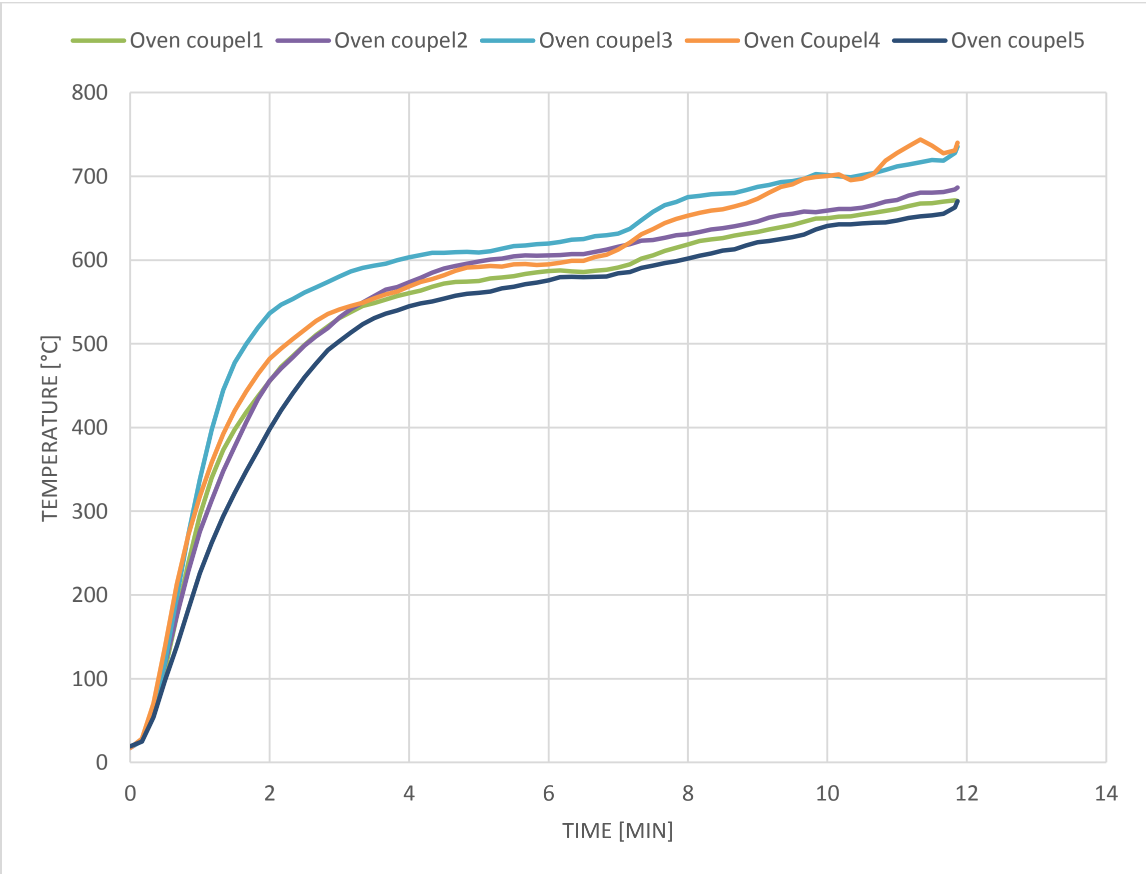
Figure 5.84 Pane N and O inside the furnace

The previous tests show that temperature difference between glass and steel supports caused thermal break. For this reason small strip of Promatect isolation is placed between these two materials, in order to decrease the temperature difference.

Figure 5.85 Promatect isolation is placed between glass and steel

5.6.2 Furnace Temperature

Five plate thermometers are used to measure the temperatures at different locations inside the furnace. The following graph present these measurements.



Graph. 5.11 Furnace temperature results

5.6.3 Pane N

Fracture

Panes N deflected considerably after 9 minutes. Thus, bricks also started to move at this time. All bricks fell down after around one minutes. Afterwards, pane deflection became enormous. And glass behaved more like plastic material. This test took around 12 minutes. Pane N did not break during this time.

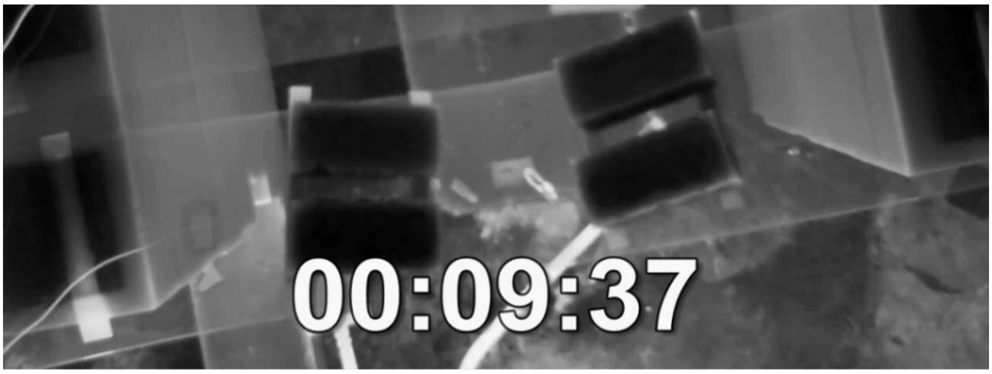


Figure 5.86 Pane N after 9.37 minutes

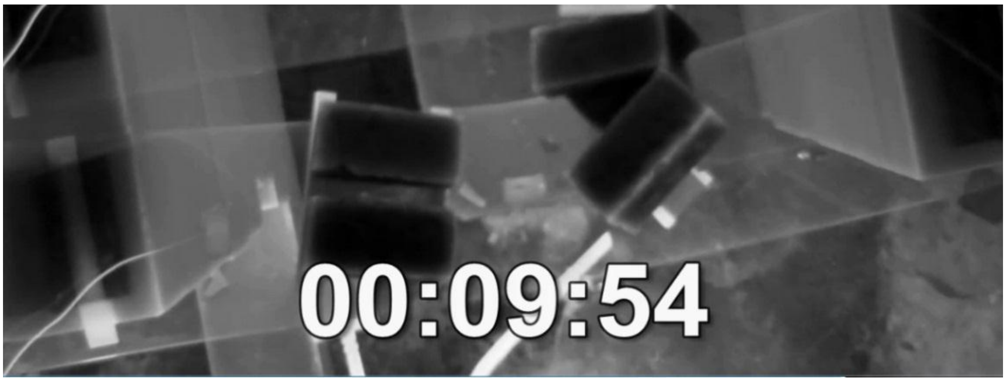


Figure 5.87 Pane N after 9.54 minutes

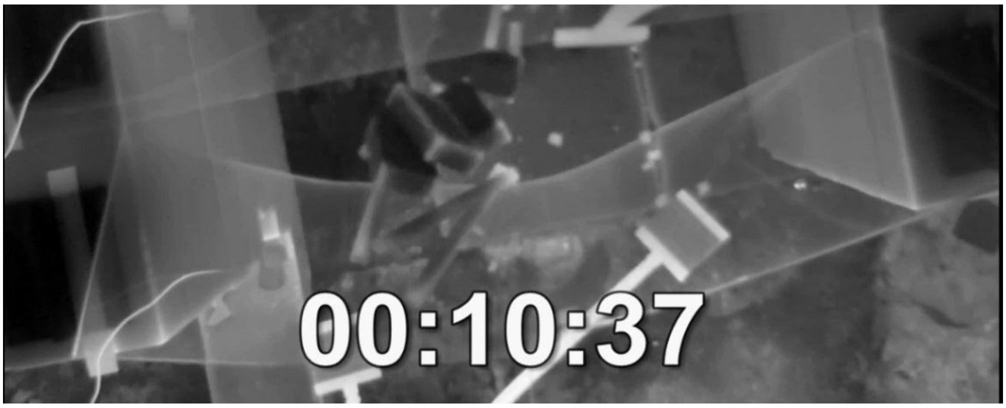


Figure 5.88 Pane N after 10.37 minutes

Figure 5.89 Pane N after 11.38 minutes

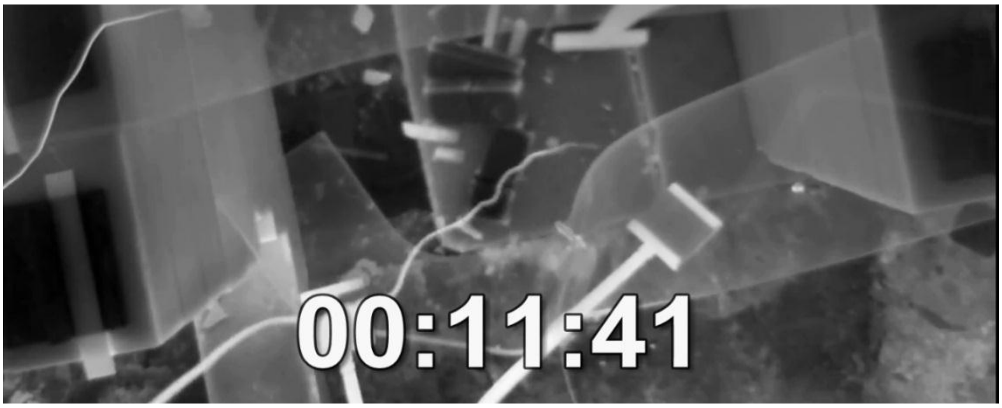


Figure 5.90 Pane N after 11.41 minutes

Figure 5.91 Pane N after 11.43 minutes

Figure 5.92 Pane N after 11.55 minutes

As it was mentioned before, pane N is not broken during test. However, the pane is fell after test. The Following figure shows pane N, when furnace was off (after test). The reason for this phenomenon is explained in the paragraph of conclusion experiment 3.

Figure 5.93 Pane N after testing

Figure 5.94 Thermal break after testing pane N

Figure 5.95 Pane fell down after thermal break

Glass temperature

One thermocouple is installed on the glass surface for measuring temperature. The following graph shows recorded temperature for glass and furnace temperatures. Fracture of glass (pervious part) shows that the glass behaves like a plastic material after 8-9 minutes. Following graph illustrates that glass temperature was around 550-600°C when glass changed its behavior. Furthermore glass temperature was lower than furnace. However glass temperature is increased steadily from the beginning to the end of test. For this reason temperature difference between glass and furnace turned to be much smaller after 12 minutes.

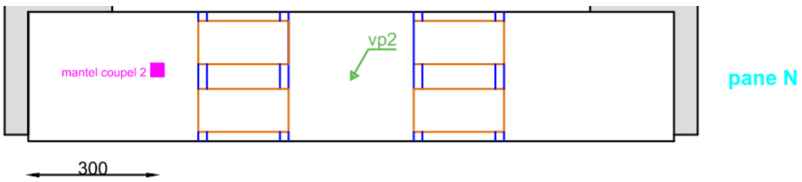
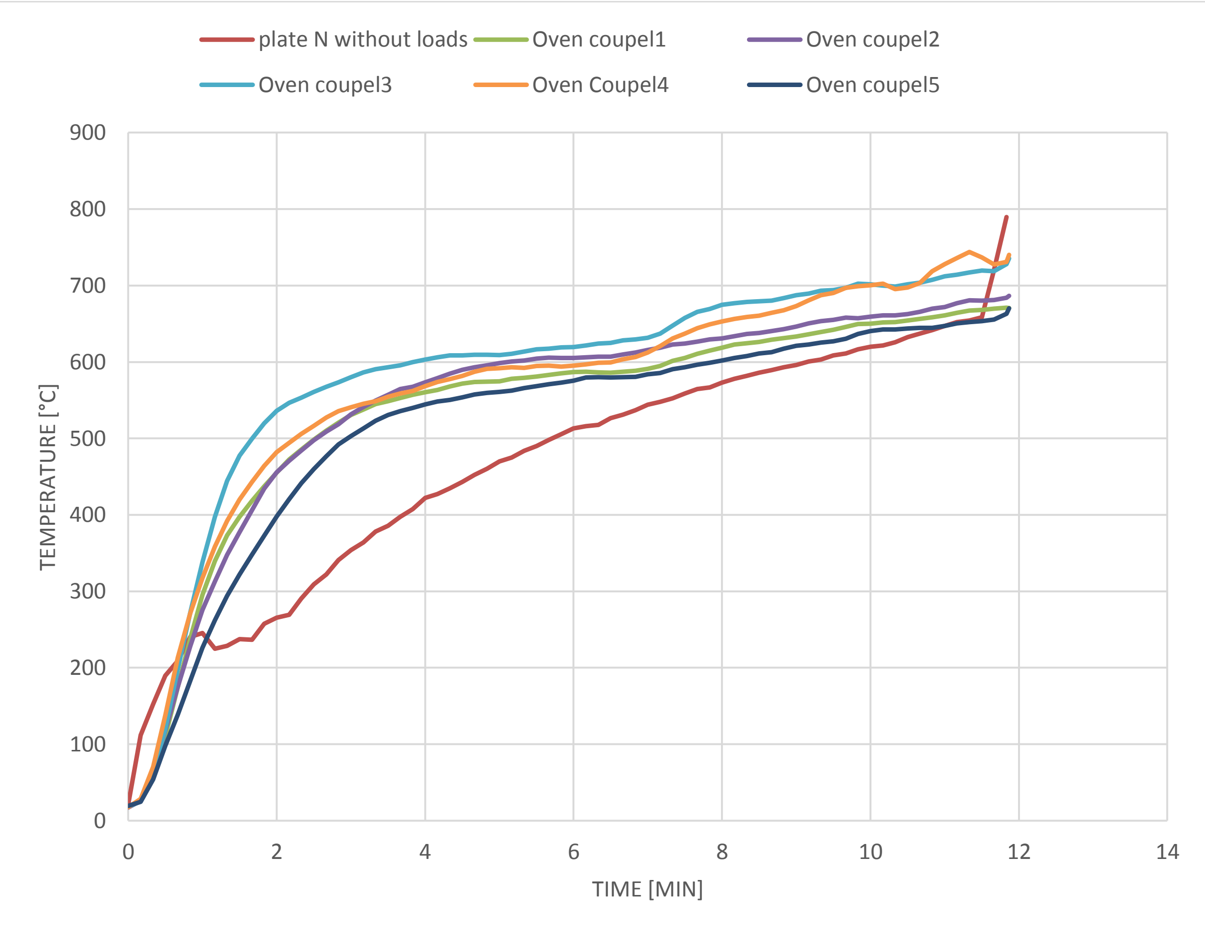


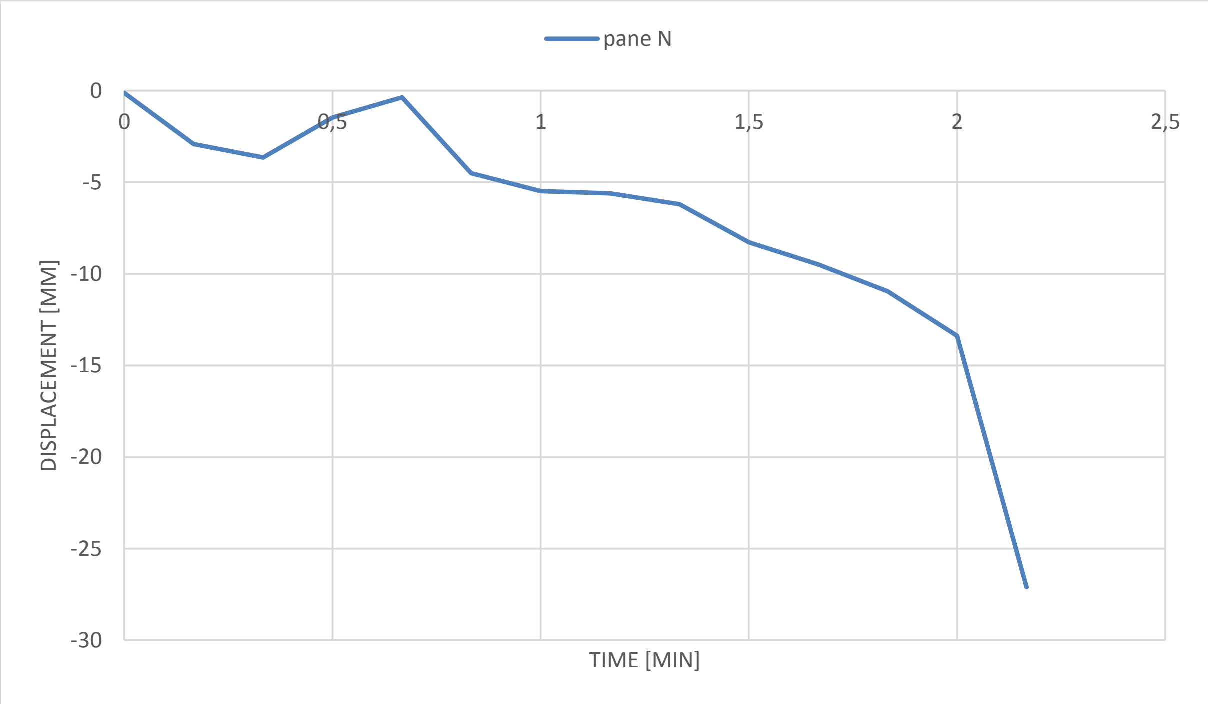
Figure 5.96 Top view pane N



Graph. 5.12 Furnace and glass temperature results

Deflection

The following graph shows that most results are negative. Which means wire is heated and extended during test and glass is not deflected as it is explained before. The wire used for pane N is heated directly with flames and it could resist fire flames about two minutes. After this time wire lost its connection. That is why deflection for pane N is measured just for 2 minutes. However, the test took about 12 minutes.



Graph. 5.13 Deflection results pane N

Figure 5.97 The wire used for pane N lost its connection after 2.20

5.6.4 Pane O

Fracture

Recorded video shows that pane O is deflected considerably after 9-10 minutes.

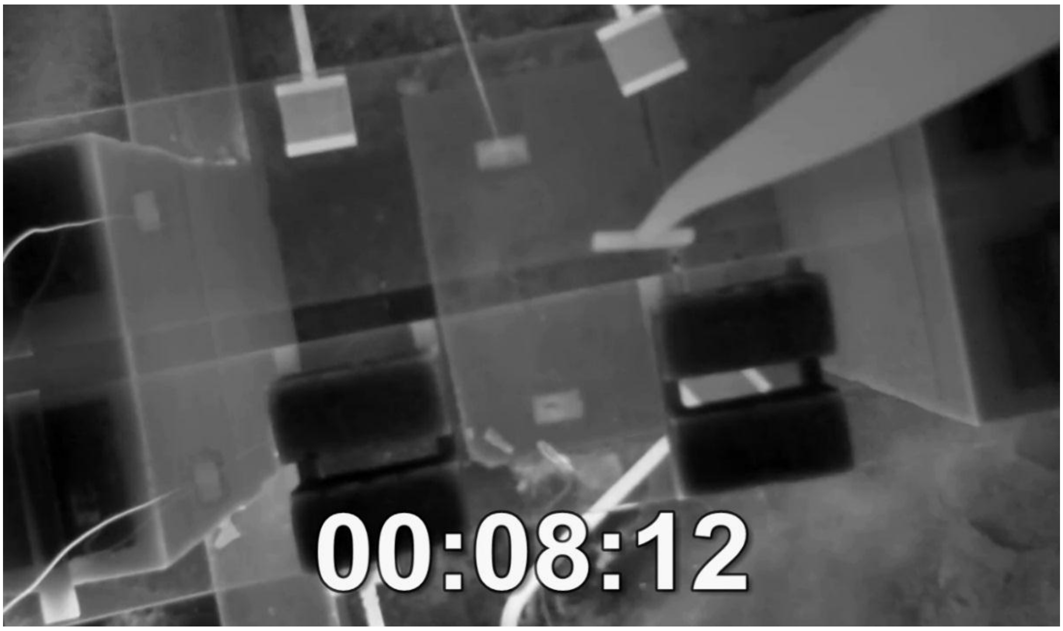


Figure 5.98 Pane O behavior after 8.12 minutes

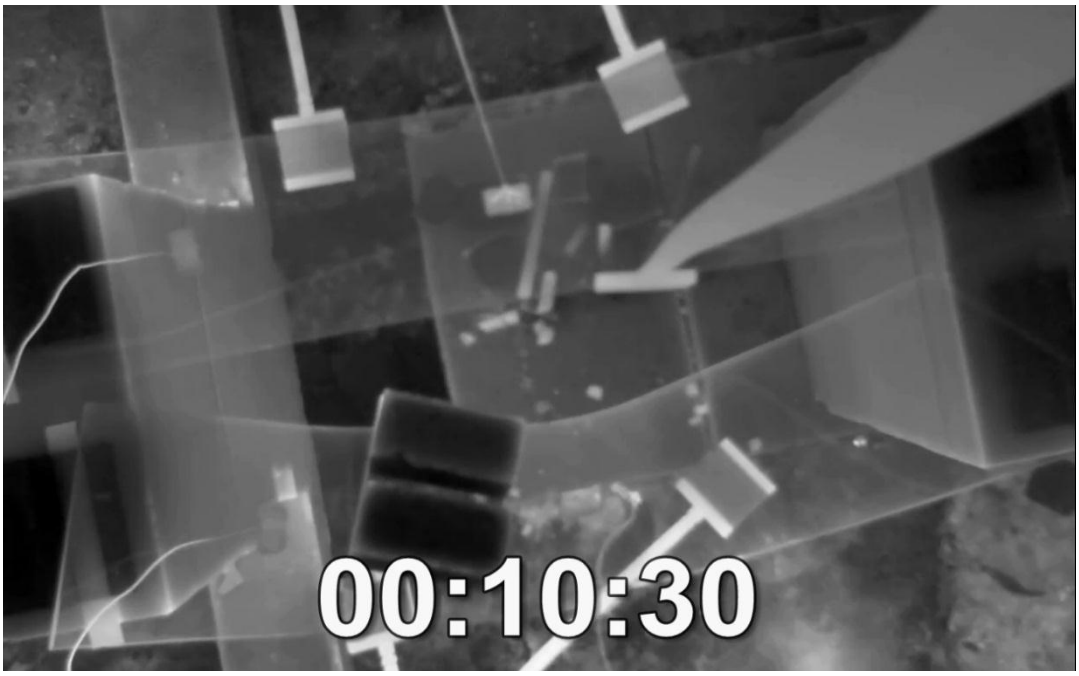


Figure 5.99 Pane O behavior after 10.30 minutes

Pane O deflected slower than pane N. Because this pane carried only its self-weight.

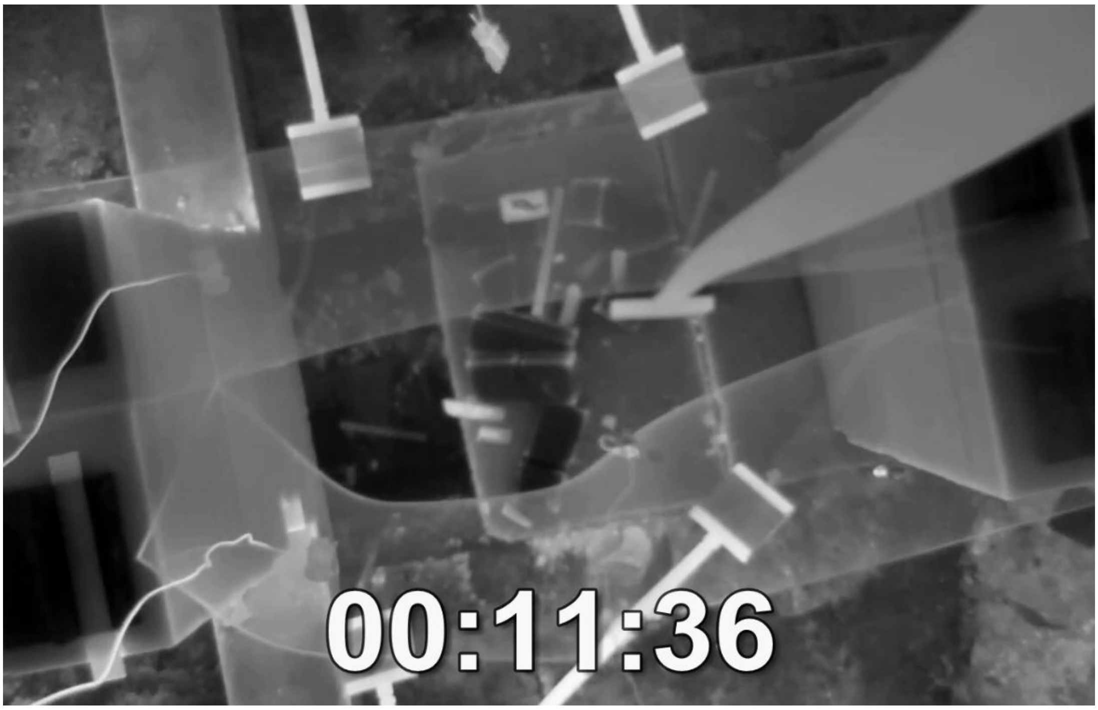


Figure 5.100 Pane O behavior after 11.36 minutes

Figure 5.101 Pane O behavior after 11:54 minutes

Pane O did not break down during the test. However, right end part of the pane, close to steel support is broken 1 minute after the test ended. The reason fot this phenomenon is explained in the conclusion paragraph of experiment series3.

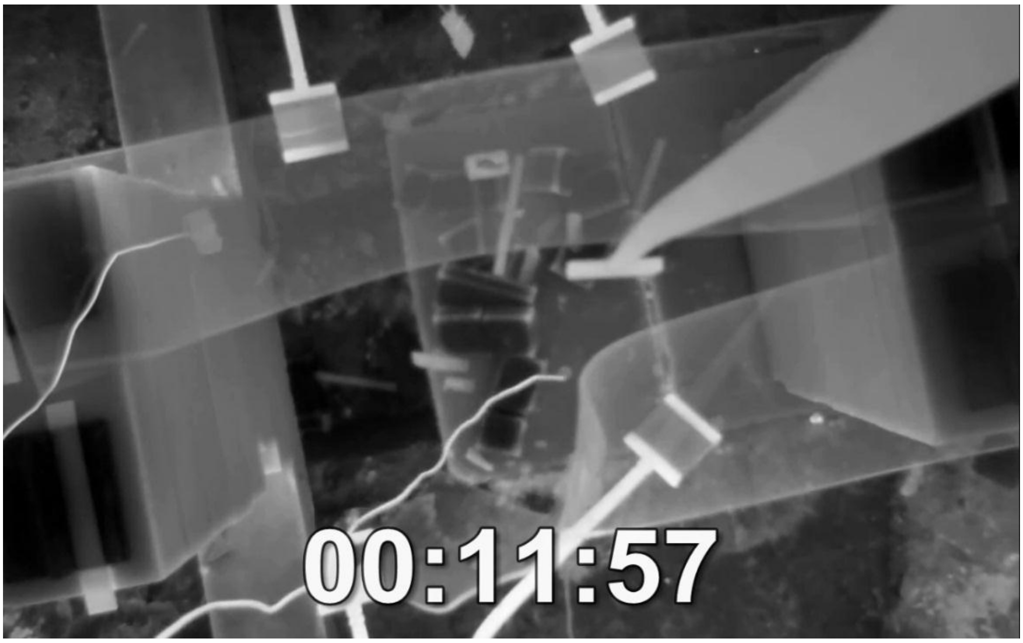


Figure 5.102 Pane O behavior after 11:57 minutes

Figure 5.103 Pane O behavior after 12:52 minutes

Glass temperature

Tmantel1 is installed on glass pane O for temperature measuring. The following graph shows results of this measuring. Furthermore data of furnace temperature and Tmantel1 (pane N) are also added, in order to compare results for pane N and O with furnace temperature.

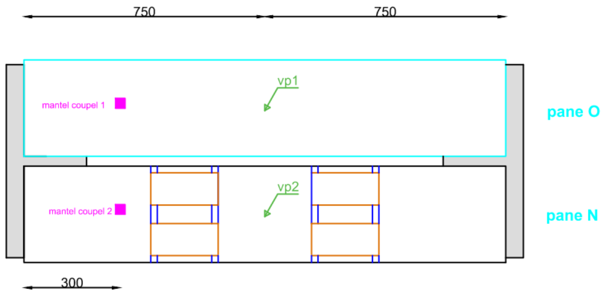
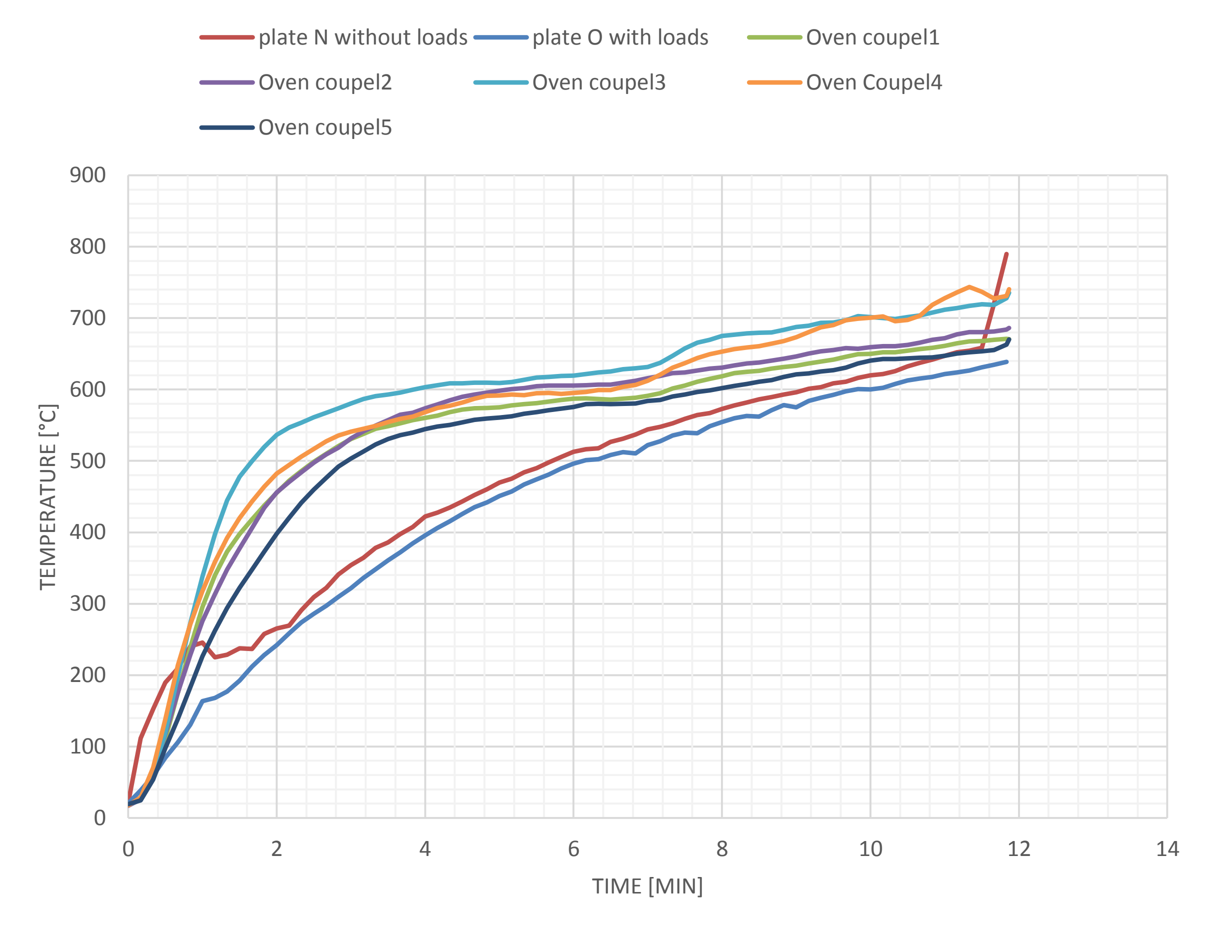


Figure 5.104 Top view panes N and O

Data results show that pane O had higher temperature than pane N. However their difference is not big. Both panes had lower temperature than the furnace. But this difference became smaller during test. Pane O deflected considerably after 10 minutes, glass temperature was around 600 °C at this moment.

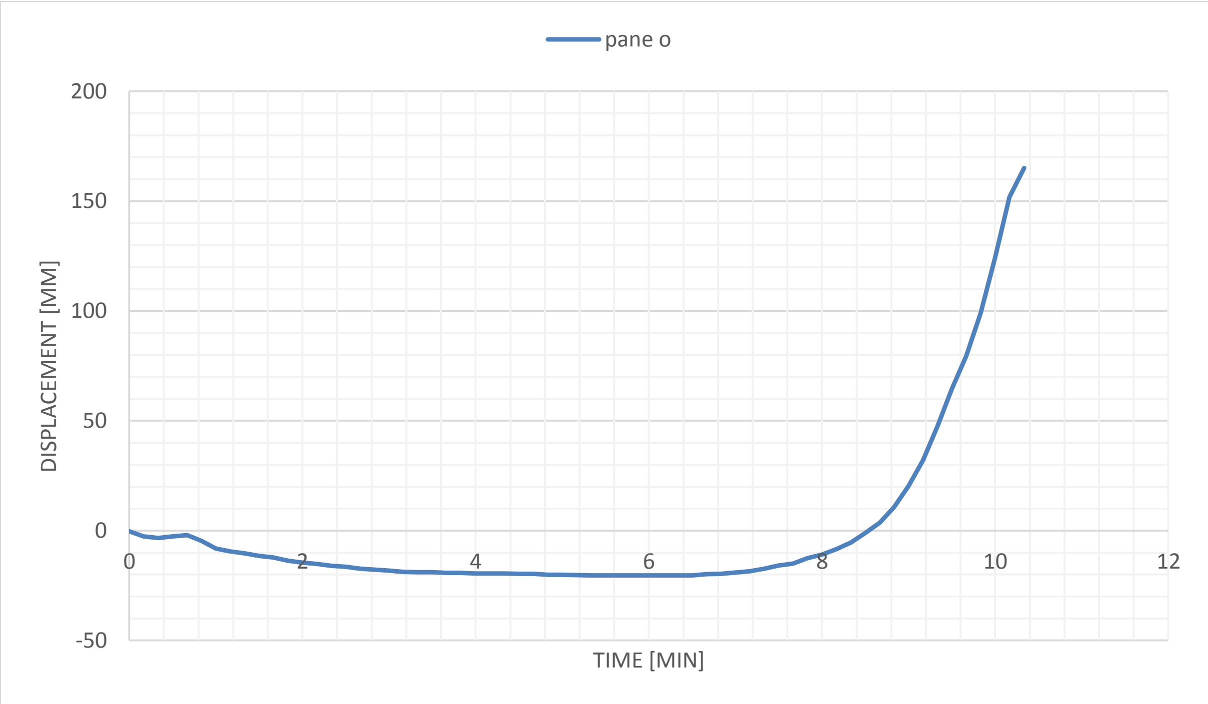


Graph. 5.14 Temperature results

Deflection

Deflection of pane O is measured in the middle point of glass. This test took around 12 minutes but deflection data is available for around 10 minutes. Because the wire used for measuring lost connection after 10 minutes. Graph shows that most of deflection results have negative value before 8 minutes. Which means the wire is extended because of heating. And the glass did not really deflect. However, results are changed to positive value after 8 minutes. In other words glass deflection started after this moment. As can been seen in the previous graph the glass temperature was around 550-600°C at the time of this changing.

Unfortunately deflection data for pane N is only available for two minutes. That is why it is not possible to see if the mentioned change (changing negative- to positive value) has occurred to pane N too. But recorded video shows that pane N deflected considerably and behaved plastically after 8-9 minutes. Glass temperature was around 550-600°C at this moment. This means that this temperature is the critical point for the glass.



Graph. 5.15 Deflection pane O

5.6.5 Results Discussion and Conclusion

Test results show that 550-600°C is a critical temperature for fully tempered glass. Glass behavior is totally changed to plastic stage after this point. Moreover, glass was not able to carry a load after this point.

Pane N and O had pre-stress due tempering process. But this pre-stress is decreased to zero after critical temperature point (550-600°C) . Panes had no pre-stress after the end of the test. Therefore panes became like an annealed glass, which is sensitive for thermal break.

Pane N is broken close to the middle part after test ends. The middle of pane was very close to the steel part of plate thermometers. After the test both material (glass and steel) started to cool down. But cooling speed for steel is faster than glass. That is why a big temperature difference is occurred between these two. And this part of the glass is broken due a thermal break.

Figure 5.105 Thermal break pane N

The pane is broken close to steel supports after test ends. The reason for this failure is exactly the same as thermal break for pane N. The only difference is that steel support played the role instead steel plate thermometers.

Figure 5.106 Thermal break pane O close to steel support

Strip of promatect isolation is used in order to prevent direct connection between glass and steel . This strip covered only small part of steel support. Deflection was big and glass moved considerably during test. For this reason small strip did not help completely and glass touched steel after some minutes.

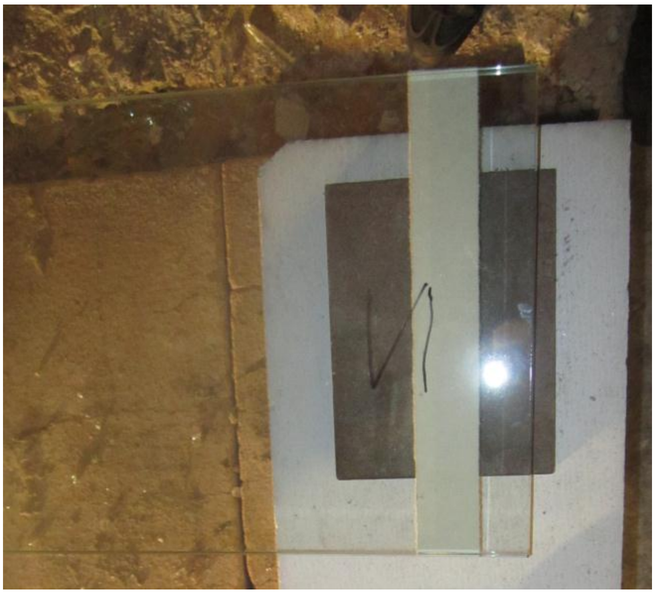


Figure 5.107 Used promatect isolation before test

Figure 5.108 Used promatect isolation after test

All part of steel support needed to be covered with promatect isolation for the next test series, in order to prevent mentioned phenomenon. For this reason, more strips with larger dimensions are used for experiments series 5 and 6.

Figure 5.109 Used promatect isolation for test series 5 and 6

As it is explained before, the wire extension was the reason for the negative values in deflection data. A reference measurement is needed to be applied to the next test, in order to check the given explanation is correct. That is why a reference point is installed for next test series.

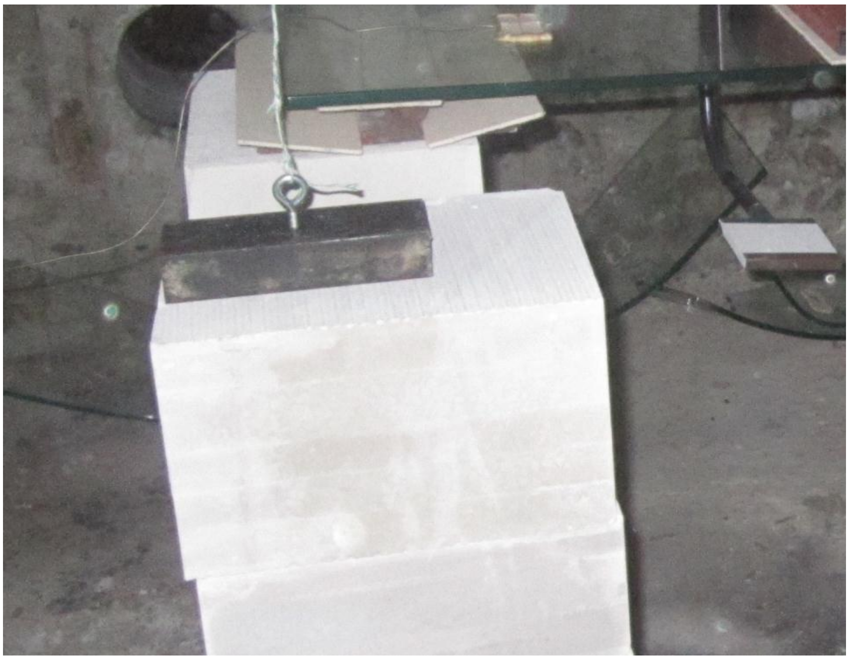


Figure 5.110 Reference point for deflection measuring

The two panes N and O are tested independently during experiment serie3. However video record shows small distance between two panes was risky that deflection of pane N caused some influence on pane O. Panes L and M are tested separately for next experiments series in order prevent this kind of risks.

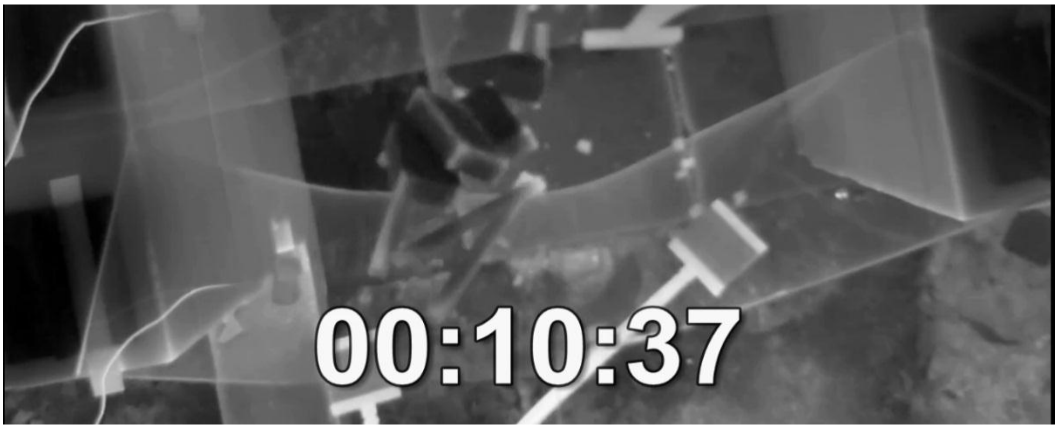


Figure 5.111 Critical distance between pane N and O

5.7 Experiment Series 5

5.7.1 Test Setup

Heat strengthened glass (pane L) is tested during experiment series 5. This pane carried its self-weight and 16 kg.

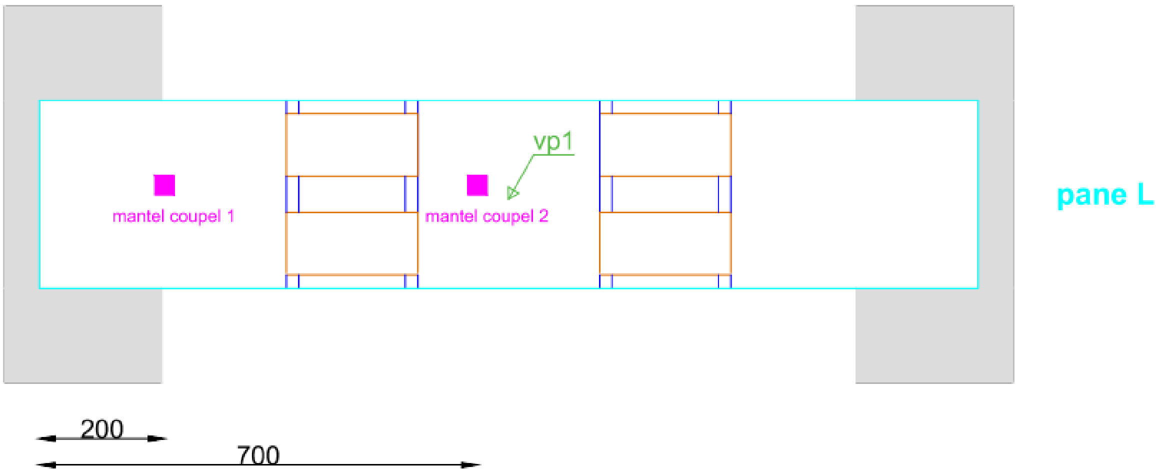


Figure 5.112 Top view pane L

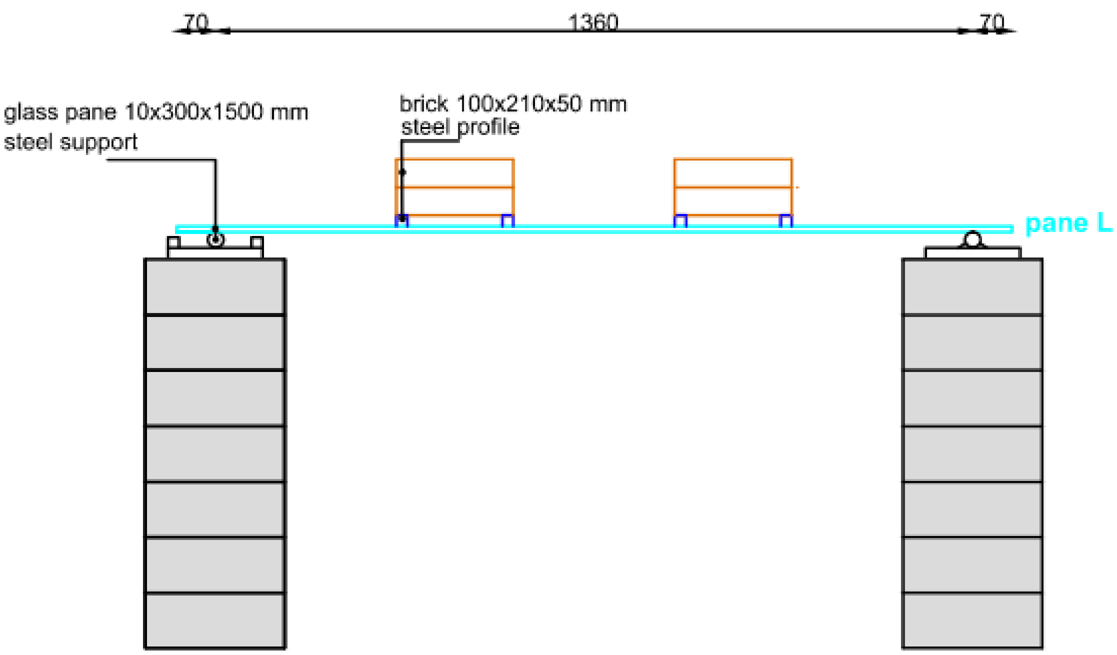


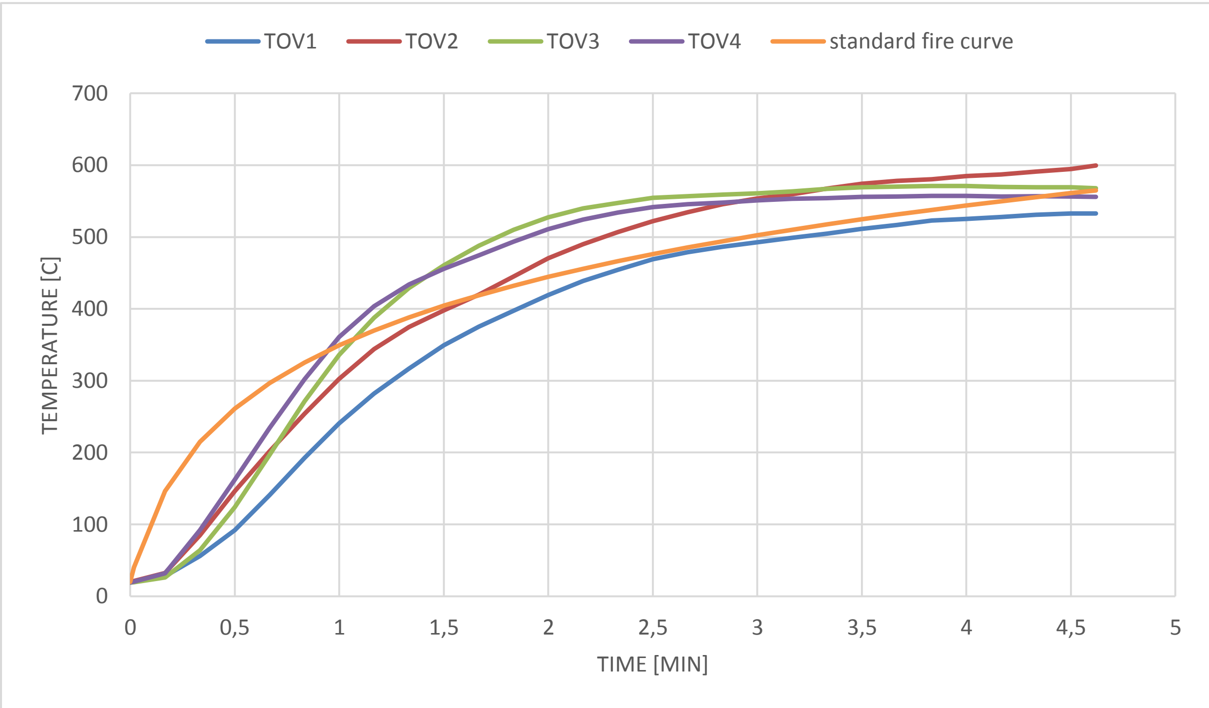
Figure 5.113 Cross section pane L

5.7.2 Furnace Temperature

Five plate thermometers are used for measuring furnace temperature.

Figure 5.114 Test setup pane L

Following graph presents results of temperature measuring in furnace. Test took 4.5 minutes. Results show that furnace temperature was very close to standard fire curve in end of test.



Graph. 5.16 Furnace temperature

5.7.3 Pane L

Fracture

Hand calculation shows that pane L should be able to carry 246 kg at room temperature. This pane carried 16 kg during test, which was 6.0% of maximum load. No thermal break occurred during this experiments series. However pane L is broken after 4.15 minutes in the middle part. This means pane L was not able to carry less than 10% of its maximum load in fire situation.

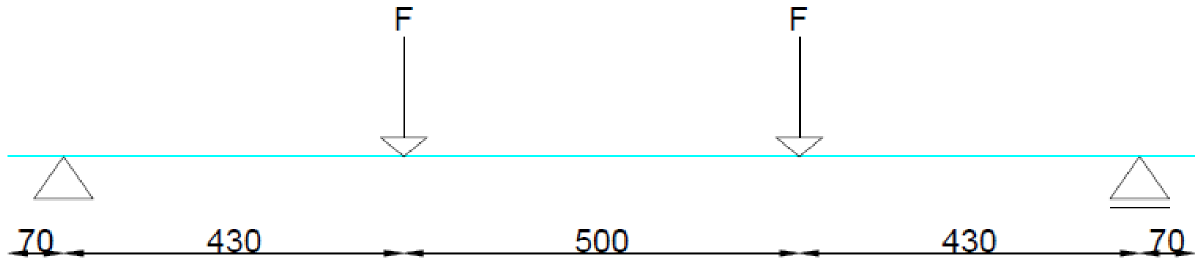


Figure 5.115 Mechanical schema glass pane

Heat strengthened glass→ σ=70 Mpa

Glass dimensions: 1500x300x10 [mm] → $W = \frac{1}{6}bh^2 = \frac{1}{6} \times 300 \times 10^2 = 5000\ [mm^3]$

$$\sigma = \frac{M}{W} \rightarrow M = \sigma \times W = 75 \times 5000 = 350000\ [Nmm]$$

$$F = \frac{M}{430 \times g} = \frac{350000}{430 \times 9.81} \sim 83\ [kg]$$

Load bearing capacity pane L at room temperature: 2F= $2 \times 83 = 166\ [kg]$

Vertical loads on pane L during test: 16 kg → 9.6% of maximum load

Glass behavior did not change to a plastic phase during this test. Recorded video does not show enormous deflection like pane N and O. However test series 3 took 6 minutes more than this test. Because of this reason glass temperature of pane N and pane O was higher than pane L at fracture moment.

Following figures show pane L before and after fracture. Glass fracture is occurred very quickly. For this reason it was not really possible to take a clear photo of failure moment. However video test 5 shows this moment clearly. Please see this video at moment 4.15.

Figure 5.116 Pane N before break

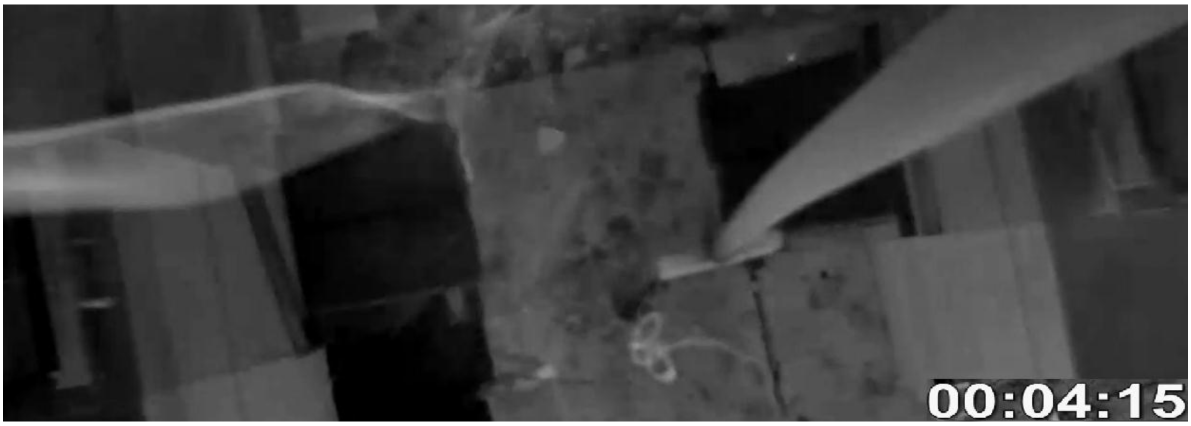


Figure 5.117 Pane N during break in the middle

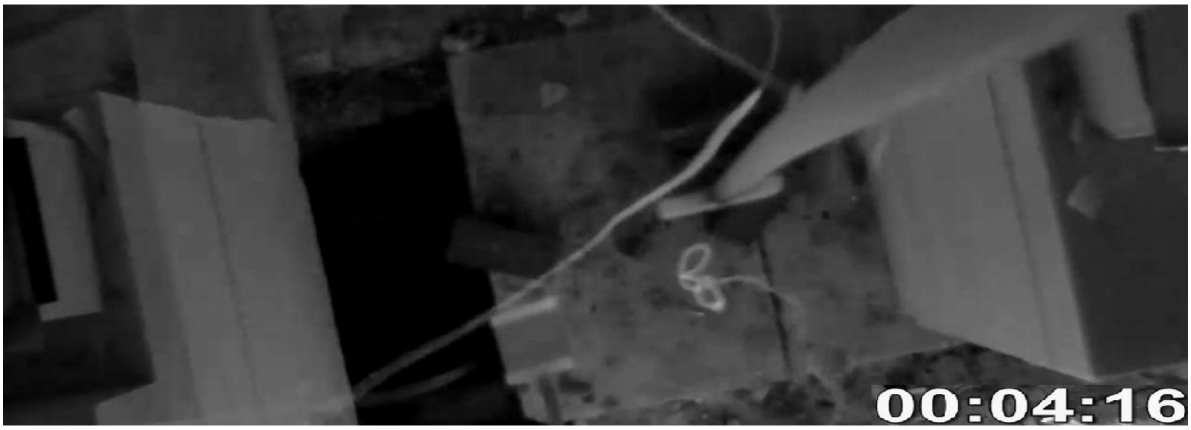


Figure 5.118 Pane N after break

Glass Temperature

Two mantel couples are installed at two different locations. Following graph shows recorded data of mantel couples 1 and 2 are very close to each other. This means glass surface had same temperature. Moreover temperature difference between glass and furnace was more than 100°C. Glass temperature was around 400°C, when pane is broken. This temperature is lower than critical temperature (550-600°C) for fully tempered glass which is observed during pervious test.

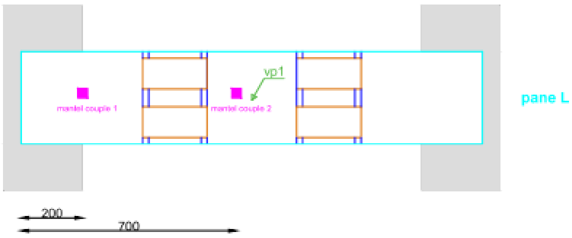


Figure 5.119 Pane L top view

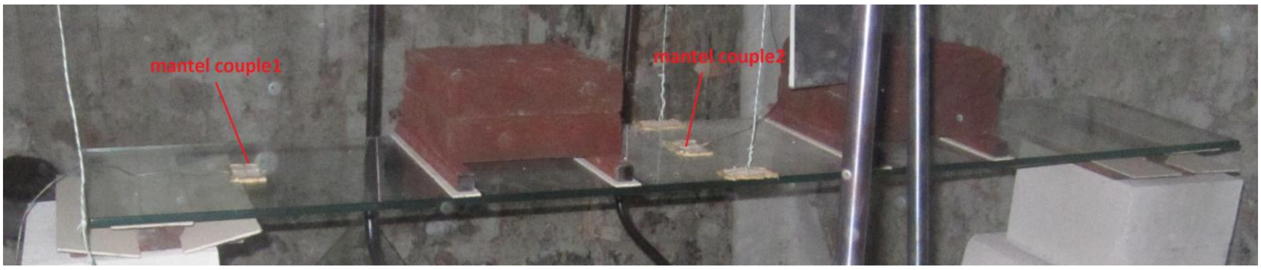
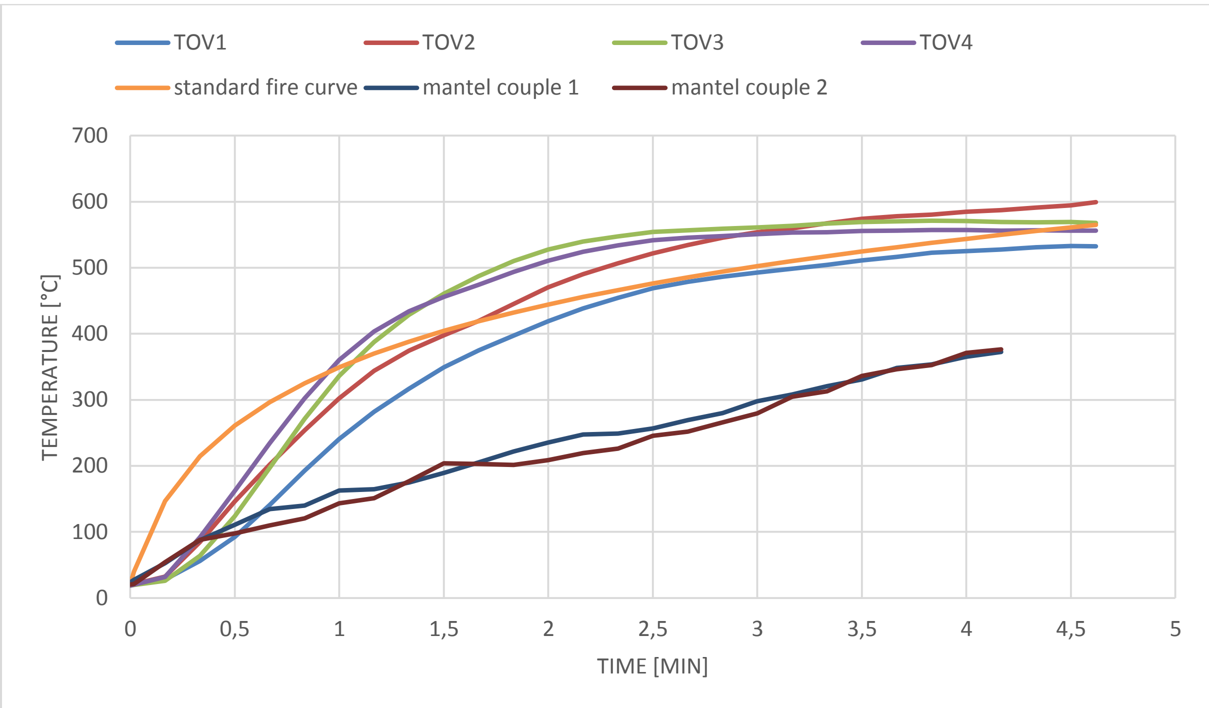


Figure 5.120 location mantelcouples



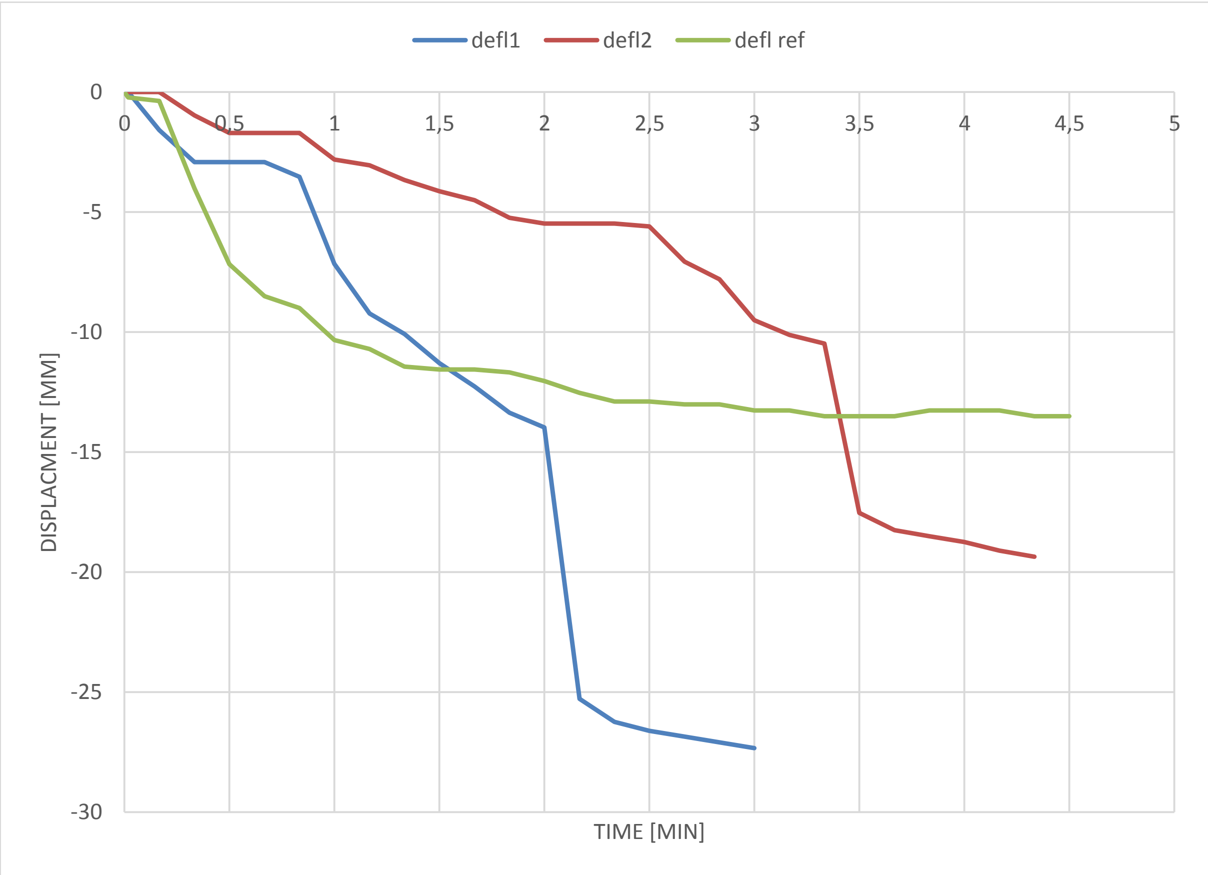
Graph. 5.17 Recorded temperature

Deflection

Pervious tests show that wire (middle for measurement) cannot resist fire flames for long period of time. Deflection is measured at two locations for pane L, in order have a reserve for data collection if one of wires lost its connection. As mentioned before, reference deflection is also measures in order to record wire extension.

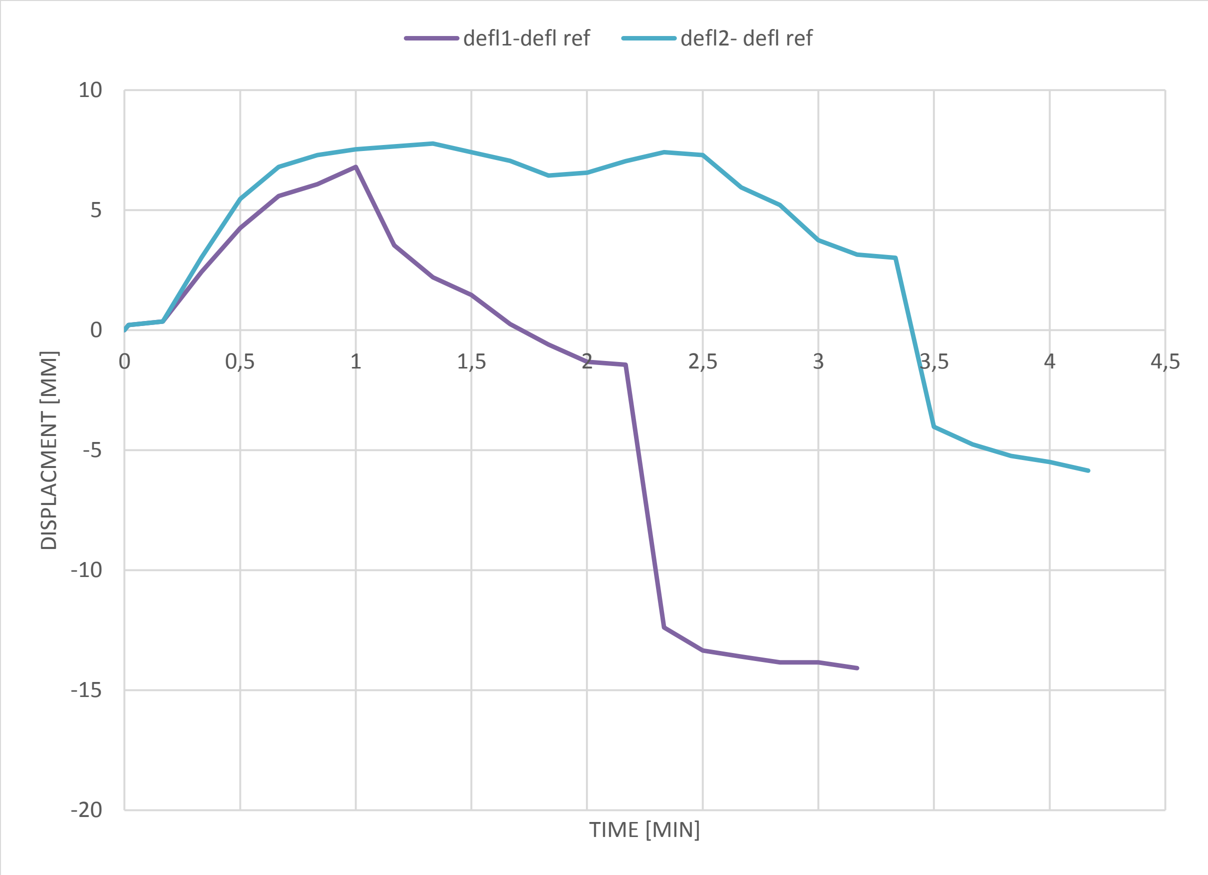
Figure 5.121 location mantelcouples

Following graph shows that all recorded data are negative values. However results of glass deflection (defl1 and defl2) are inclusive wire extension. Recorded data for reference deflection show extension of wire is considerably. Moreover it proves that explanation for negative value during pervious tests was correct.



Graph. 5.18 Recorded deflection inclusive wire extension

Glass deflection exclusive wire extension (delf – refrence defl) are given in following graph. Glass deflections shows both positive and negative values.



Graph. 5.19 Recorded deflection exclusive wire extension

Location of points of delf 1 and defl2 were symmetric. Which means deflections of this points should be almost same. However graph shows this difference is increased after 1 minutes. One explanation can be given for this difference. Pane L is heated with flames from right and left. But graph for furnace temperature shows that temperature around location of defl1 was lower than defl2. Which means wire extension of defl2 was more than defl1 one.

Moreover graph shows that deflection data is changed to negative values after 2 and 3 minutes for deflection point 1 and 2 respectively. Locations of this points and defl ref are illustrated in following figure. As can been seen in this drawing point 1 and 2 were more close to fire flames than location of defl ref. For this reason wire extension of this wires is larger than other one. Furthermore recorded video show clearly that glass is deflected downwards, which means glass deflection should be positive value. In other words the available deflection results do not present exact deflection of glass and these are not reliable.

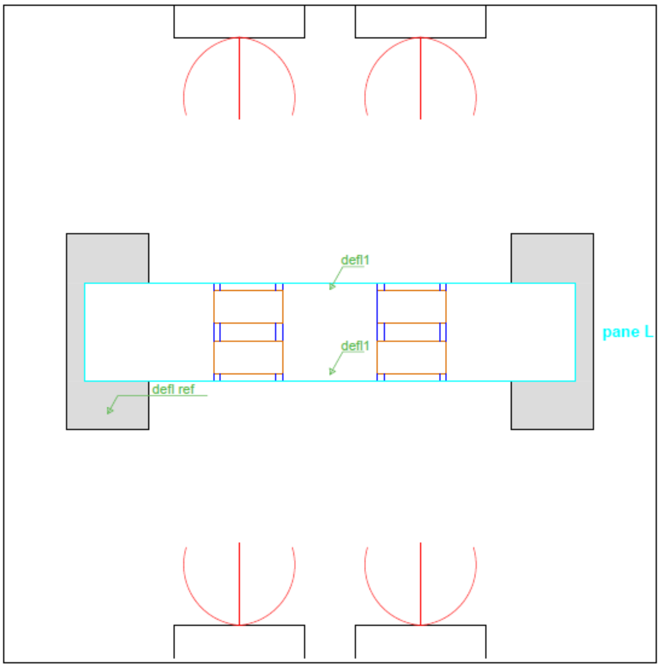


Figure 5.122 Top view fire flames in the furnace

5.7.4 Results Discussion and Conclusion

Pervious test shows that distance between pane N and O was critical. For this reason pane L and M are tested separately. However this panes were both heat strengthened glass. Conclusion of testing pane L and M are given together after next test explanation.

5.8 Experiment Series 6

5.8.1 Test Setup

Pane M is tested during last test series. Glass type of this pane was heat strengthened and carried only it self-weight.

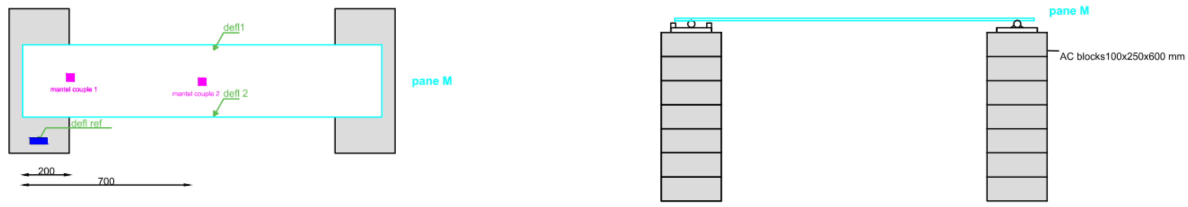


Figure 5.123 Test setup for pane M

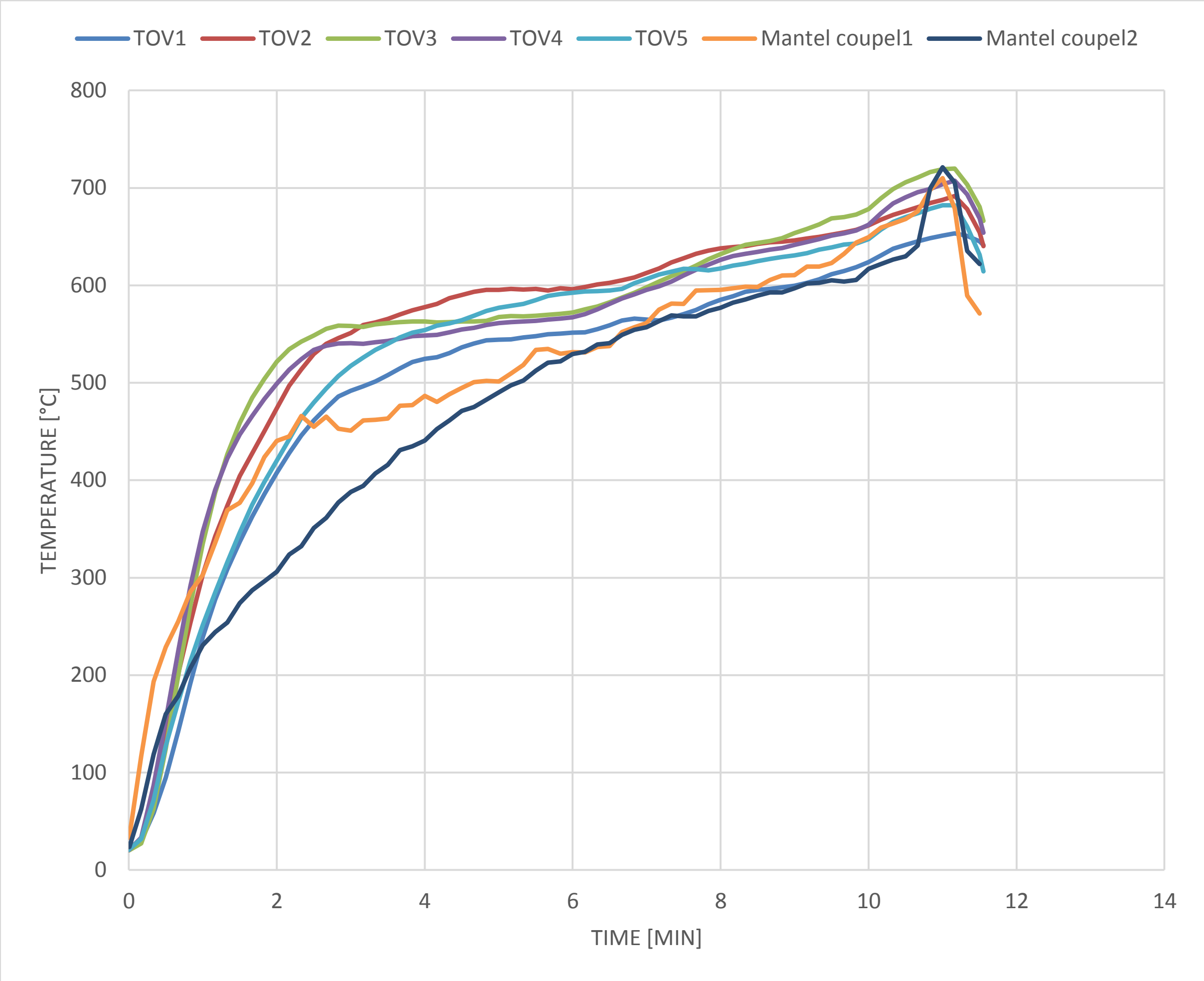
Figure 5.124 Pane M

Efcetis needed furnace for other testing. For this reason test series 6 is performed 3 hours after pervious test series. Unfortunately was not possible to give more time for furnace cooling. Temperature of inside furnace is measured before start, in order to check if furnace is cooled down and ready for new test. Recorded temperature showed initial temperature of furnace was same as pervious test. However this temperature is recorded 5 minutes after door of furnace is closed. It is possible that initial temperature was higher.

Figure 5.125 Recorded temperature before start test 6

5.8.2 Furnace Temperature

Five plate thermometers are also used for measuring furnace temperature during this test. Locations of this thermometers were exactly same as pervious test. Following graph shows results of this measuring and glass temperature which is explained in next paragraph.



Graph. 5.20 Recorded temperature

5.8.3 Pane M

Glass Temperature

Two mantel couples are used for measuring glass surface temperature. Location of this mantel couples are illustrated in setup drawings. Results show glass temperature difference between glass and furnace was smaller than pervious test. As it mentioned before furnace had not enough time to cool down. This can be reason of this temperature increasing.

Fracture

Pane M is deflected enormously after 10 minutes. One of the steel support was rol, which this gave pane freedom to move horizontally. For this reason glass moved considerable after 10 minutes and finally pane fell down. This means glass could resist more if fixed support are used.

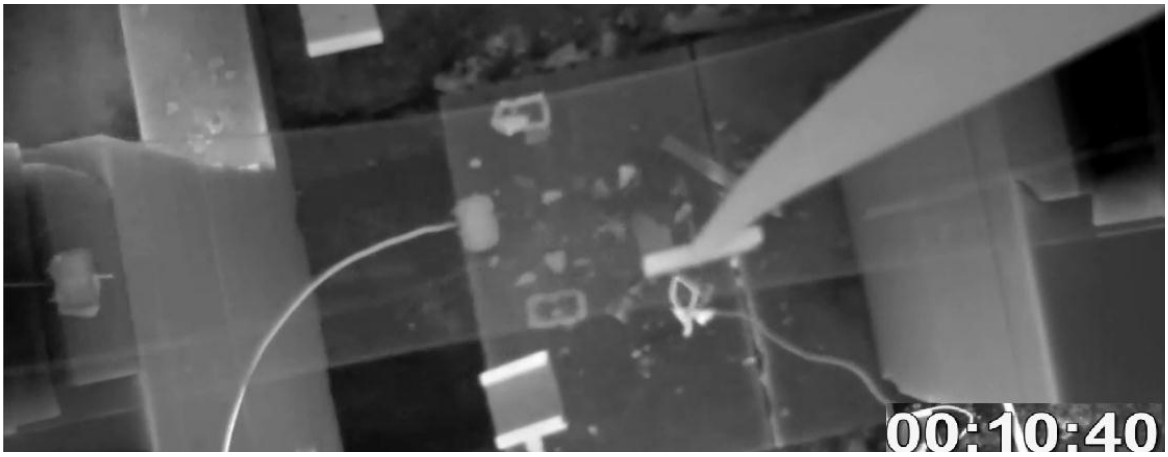


Figure 5.126 Pane M before fail after 10:40 minutes

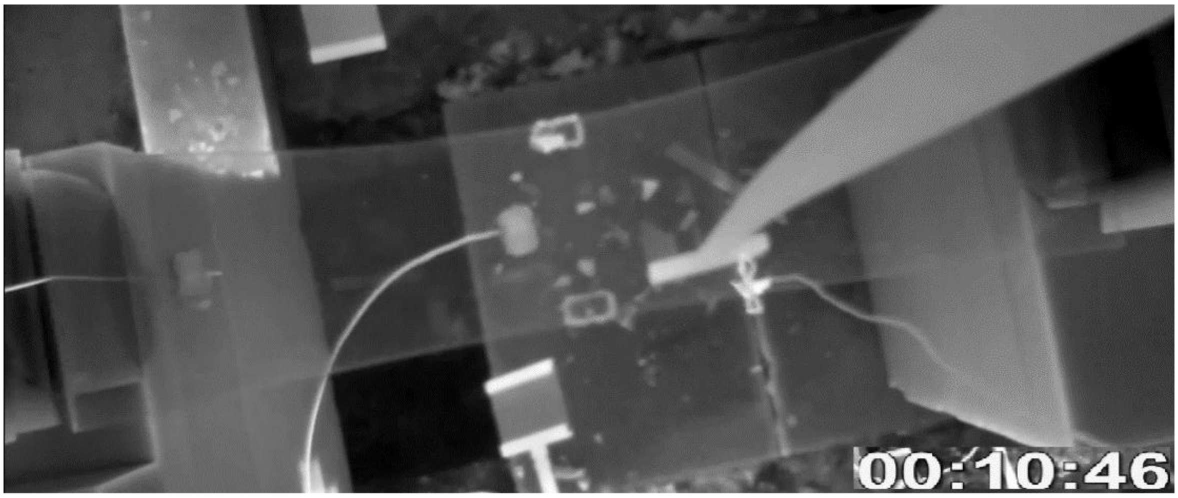


Figure 5.127 Pane M before fail after 10:46 minutes

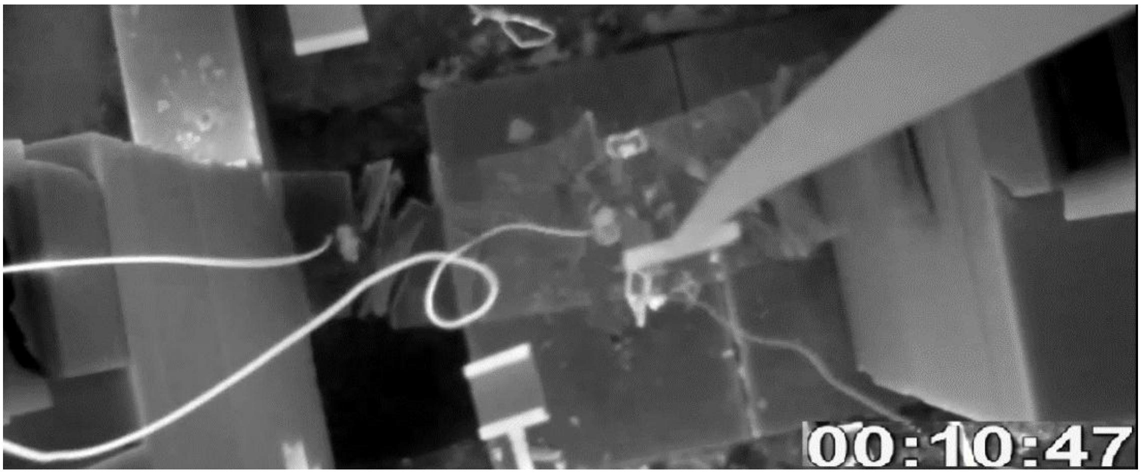
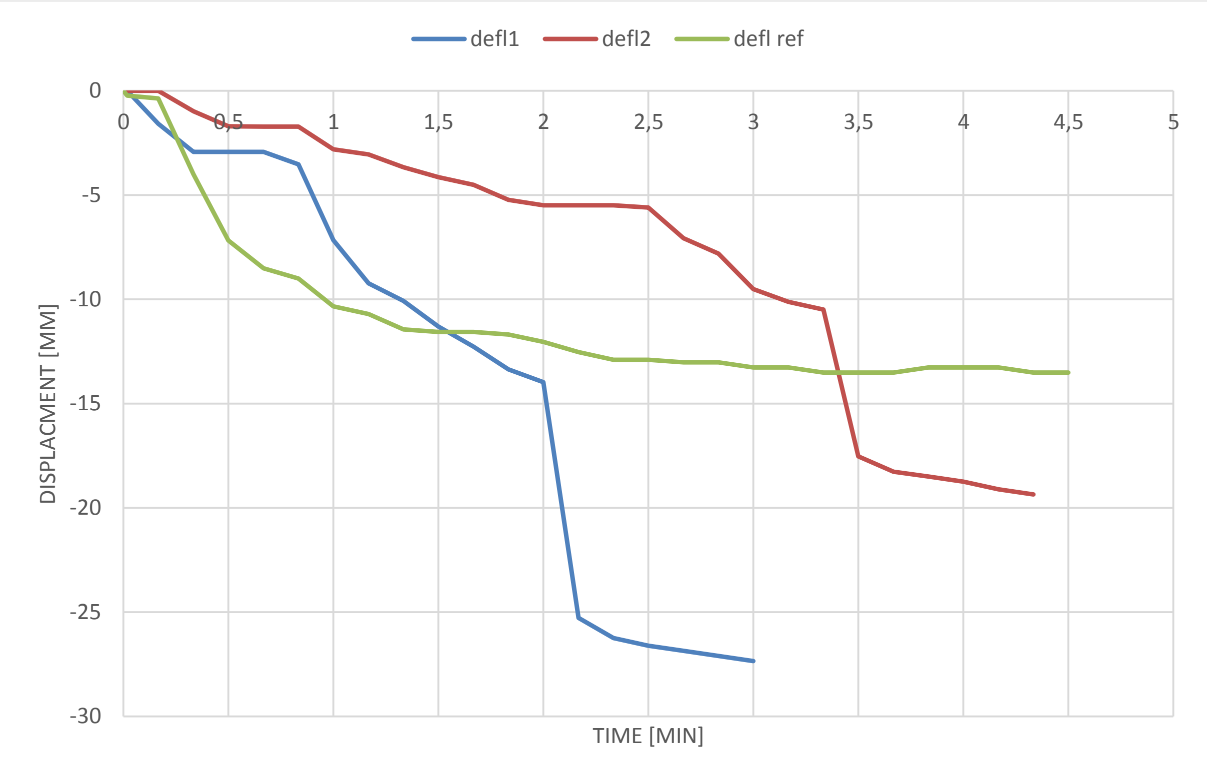


Figure 5.128 Pane M after fail minutes

Deflection

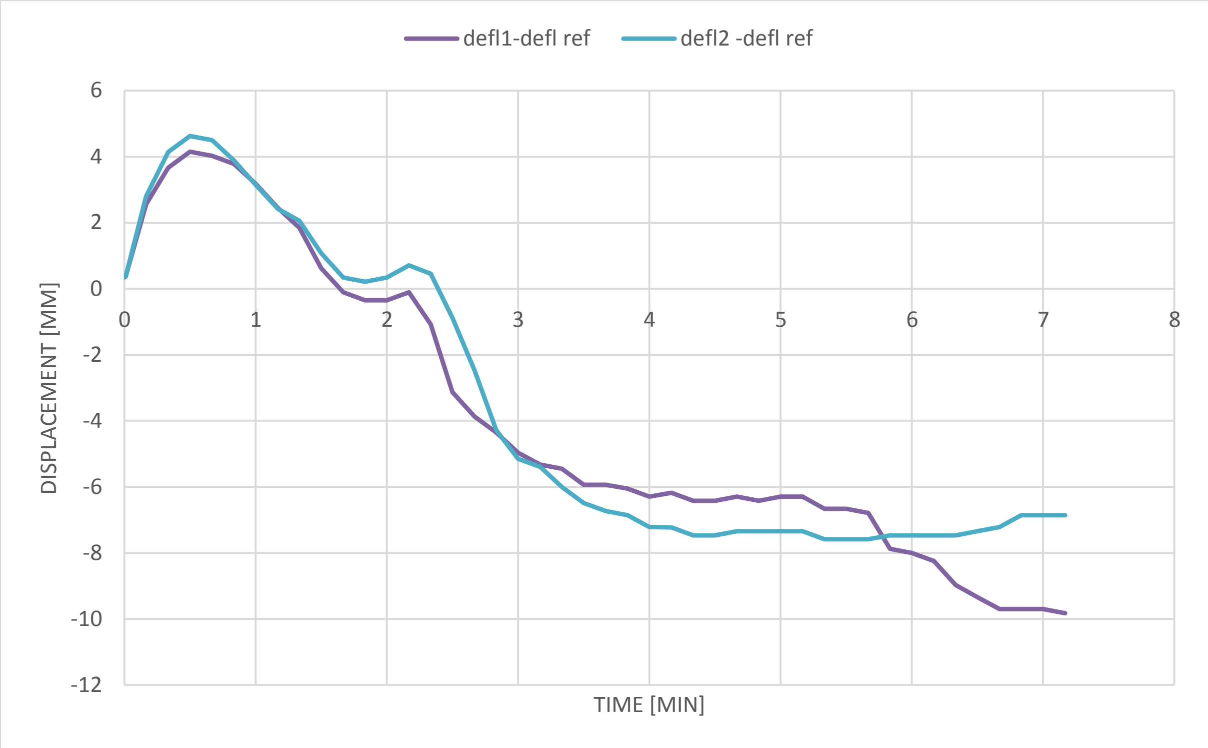
Deflection is measured at two points exactly same as pervious test. First graph show deflection of this points inclusive extension of wire.



Graph. 5.21 Recorded deflection inclusive wire extension

Glass deflection exclusive wire extension (delf – refrence defl) are given in following graph. Glass deflections shows both positive and negative values. Test took more than 10 minutes. But wire lost its connection with glass after 7 minutes. For this reason no data is available after this moment. As it explained it for previous test, wire extensions at measured points (defl1 and defl2) were bigger than extension of reference point. Because reference point is heated minder. It means that this graph does not present exact deflection of glass. And the results are not reliable.

Moreover available data is only for first 7 minutes. Recorded videos shows clearly that glass deflected downwards (positive value) after 8-9 minutes. Please see video test 6 for this observations. Glass temperature was around 550-600°C at this moments. This temperature was also critical during test series4. Fully tempered glass panes started to behave like plastic material when glass temperature were around 550-600°C.



Graph. 5.22 Recorded deflection exclusive wire extension

5.8.4 Results Discussion and Conclusion

Test results shows pane L was not able to carry less than 10% of its maximum load which is calculated for room temperature. It means that glass in combination with fire became very weak material.

Test experiments series 4, 5 and 6 proved that temperature 550-600°C is very critical for different glass types. Glass temperature needed to be lower than this temperature in order to able for fire resistance more than 10 minutes.

Using promatect isolation between glass and steel was useful to prevent thermal break during and after test. However this was a temporary solution for this test and cannot be used in real situation.

Deflection results were not exact. But this information shows that glass behavior changed considerably when glass get temperature of 550-600°C.

6 Finite Element Model for Efectis Tests

One of the questions in this thesis is to see if it is possible to make a correct finite element model about behavior of the glass during fire. In order to answer this research question, the model of pane A is made in DIANA software. In the following paragraphs the structural analysis will be explained. Firstly, the modeling and the load calculation will be presented and following, the analysis results.

6.1 Geometry and Boundary Conditions

Auto Cad drawings are used for making the geometry in the Finite Element Model (DIANA). This drawing show that the beam's geometry and its boundary conditions.

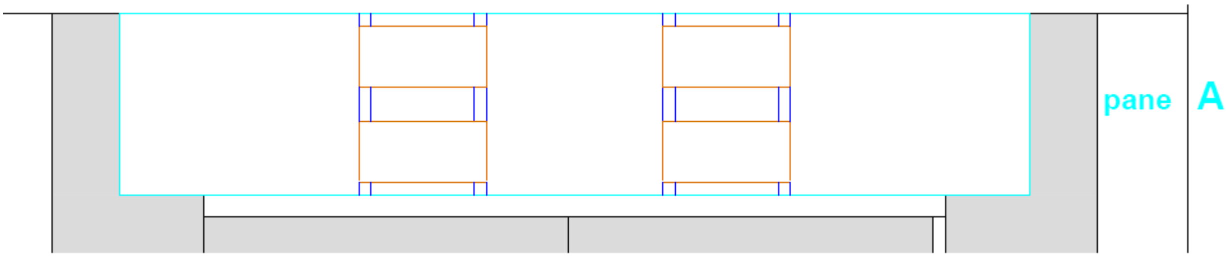


Figure 6.1 Top view pane A

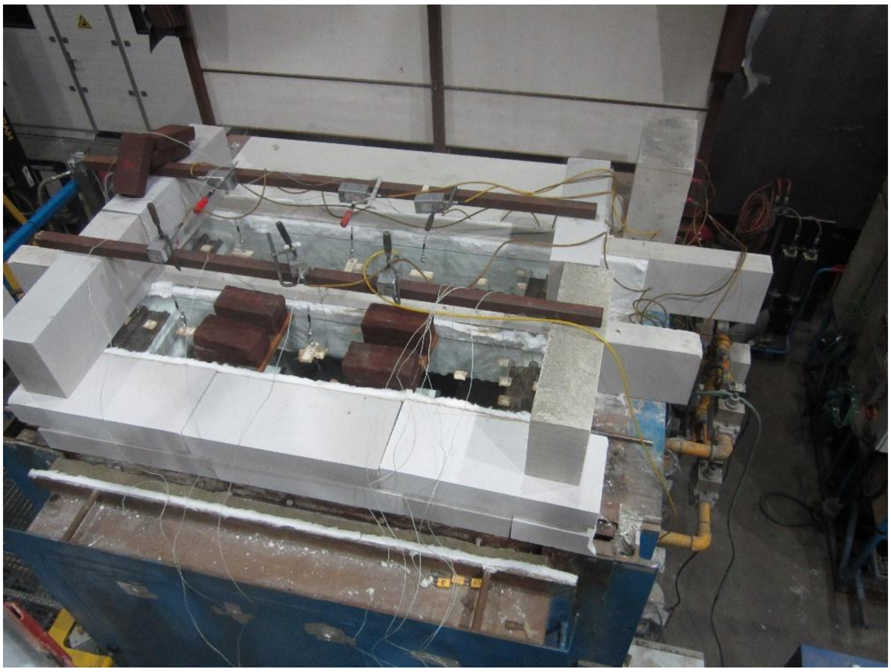


Figure 6.2 Setup test series1

As first step, a 3D beam model was made in DIANA. This beam consists of one glass layers (10 mm) and the beam has 1.5 meter length and 0.30 m width. This is a symmetric beam, so quarter of the beam was not modeled. Instead boundary conditions were applied in the middle of the beam.

Two supports were added to the beam. The beam's left side has a rol support which means it is free in the x-direction and fixed in the z-direction. But the middle of the beam is fixed in the x-direction. In other words its ux=0.

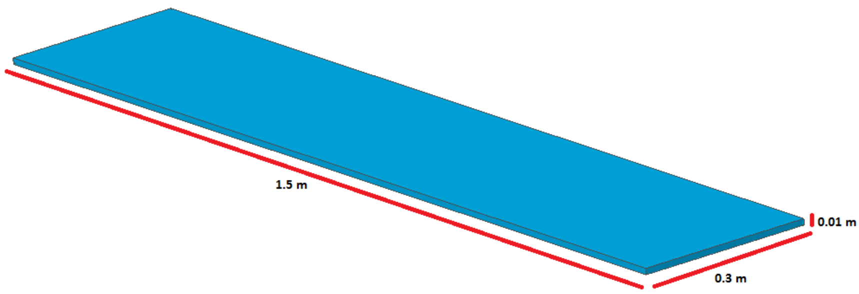


Figure 6.3 Pane geometry

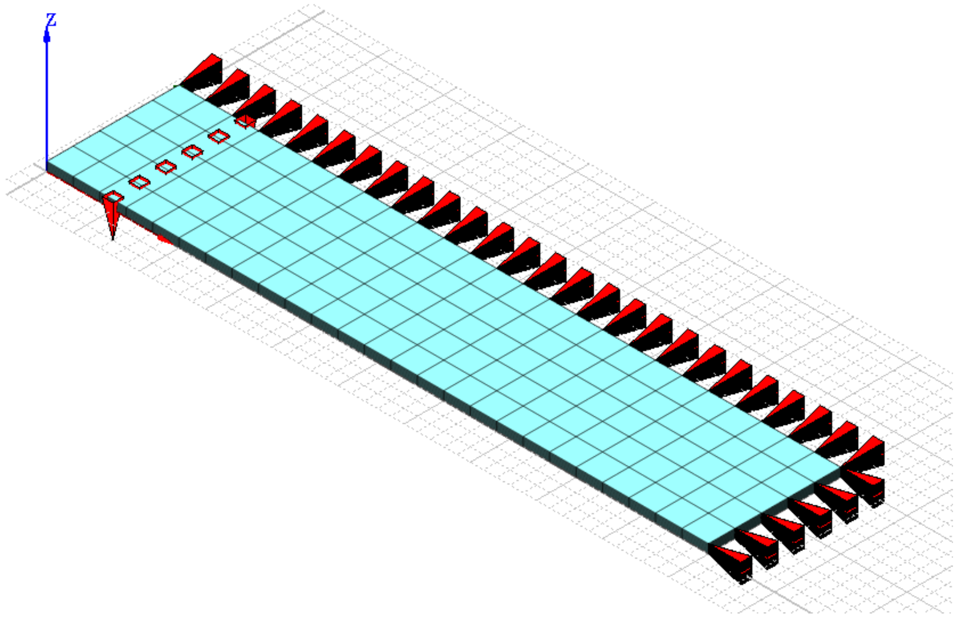
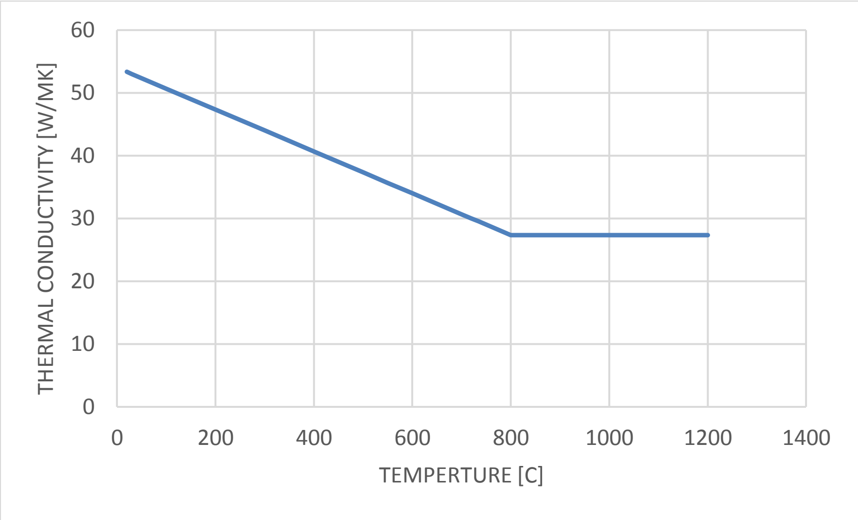
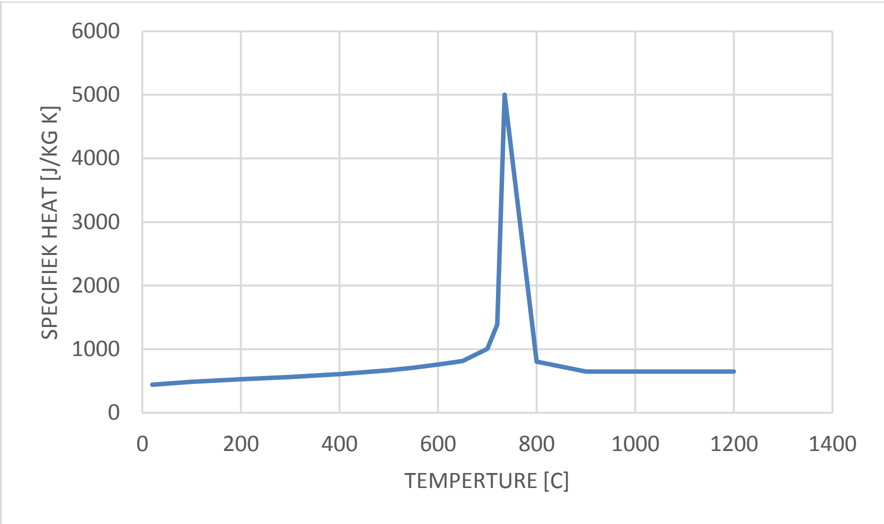


Figure 6.4 Boundary conditions

Steel support are model for this beam. Thermal properties of steel are added to them model. And low value for E modules is used. Because steel support had only thermal influence in connection with glass pane.



Graph. 6.1 Steel Thermal conductivity



Graph. 6.2 Steel specifiek heat

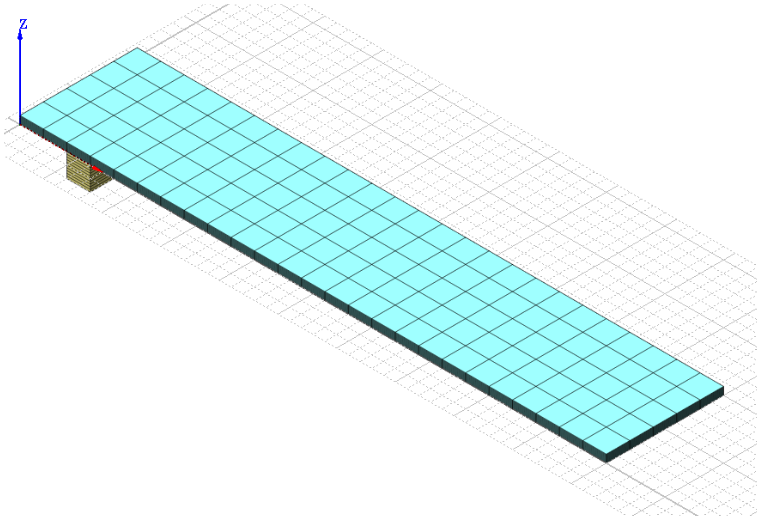


Figure 6.5 Location steel support

6.2 Mesh

The element type is used for the glass layers and the interlayers is HX24L. HX24L indicates that it is a 3D brick element with 8 nodes. Its active degrees of freedom is 24 dof's which means 3 dof's ux, uy, uz per node. The element size was set to 30 x 30 x 1 mm.

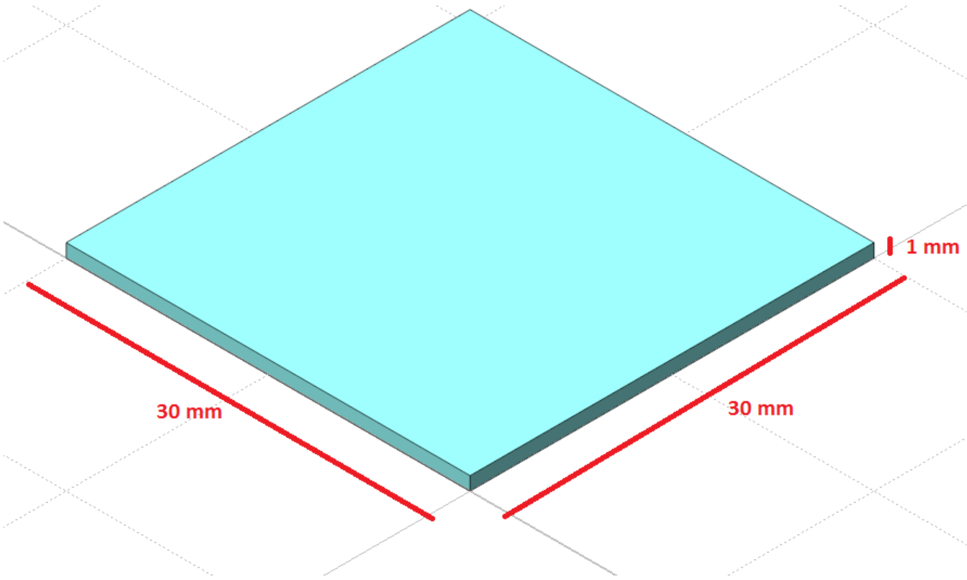


Figure 6.6 Mesh element

6.3 Section Properties of the Glass Beams

The material properties of soda lime glass are determined for this stage. Which were presented in the thermal and the mechanical properties' chapter. In addition, the Poisson's ratio of 0.23 is considered for glass at room temperature. The mass density of glass is given 2500 kg/m3.

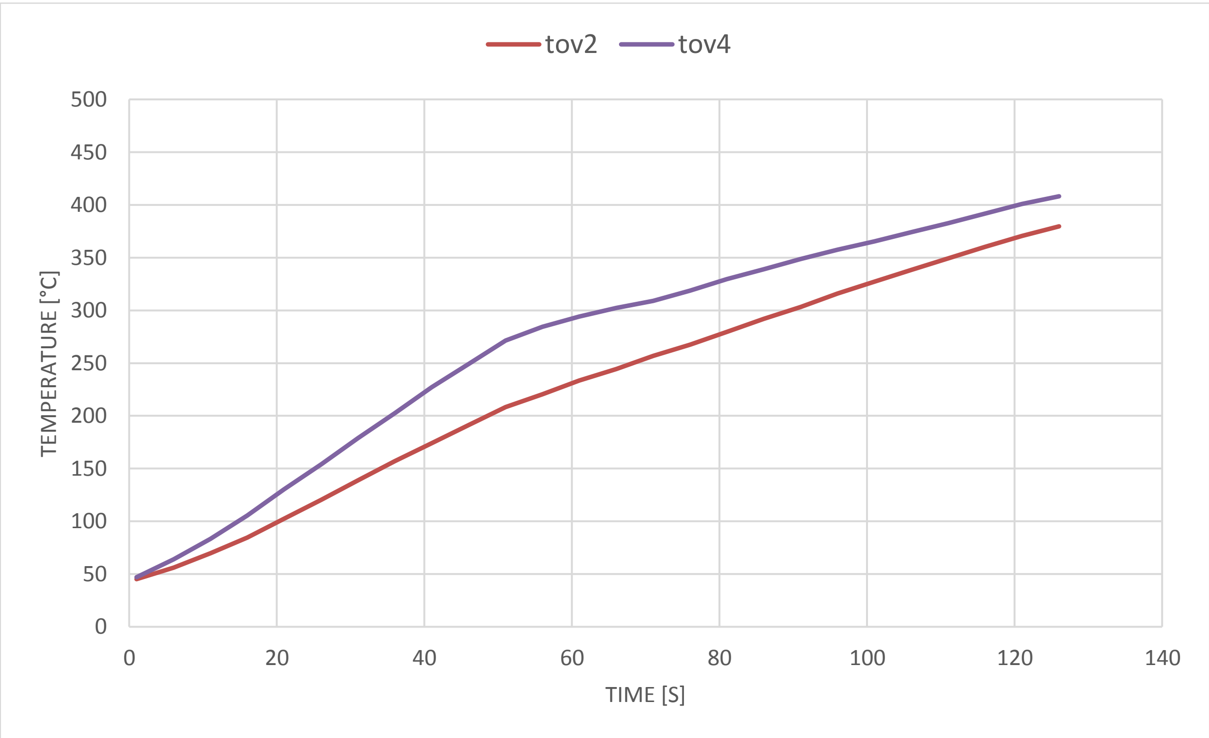
6.4 Loads

Six kinds of loads cases were considered for the beam modeling in DIANA.

- 16 kg brick
- beams' self-weight
- oven temperature convection
- oven temperature radiation
- initial temperature
- air temperature convention
- air temperature radiation

6.5 Furnace Temperature for Model

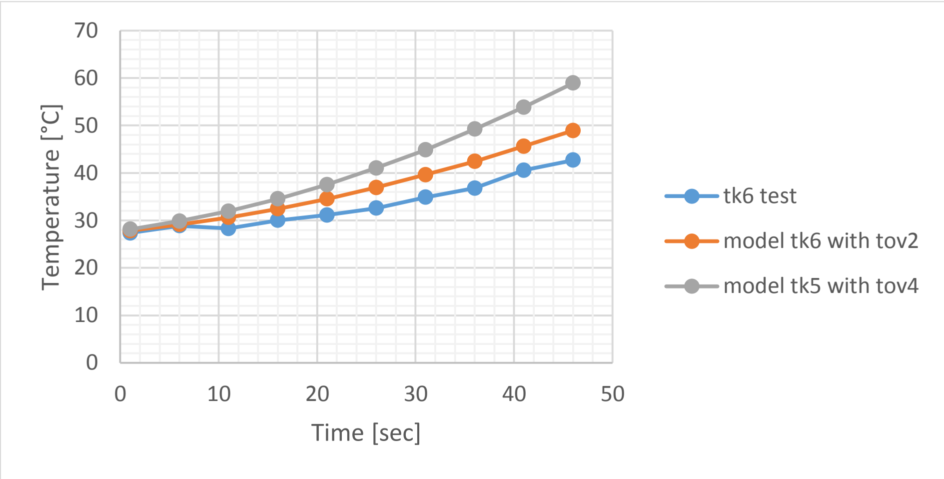
As mentioned before this test took only 111 seconds and this period of time was not enough to get a standard fire curve. It means the standard fire cannot be used to make the model. Otherwise the test will result in a wrong estimation of glass behavior. For this reason measured furnace temperature of experiments series 1 is added to the model.



Graph. 6.3 Used furnace temperature for in the model

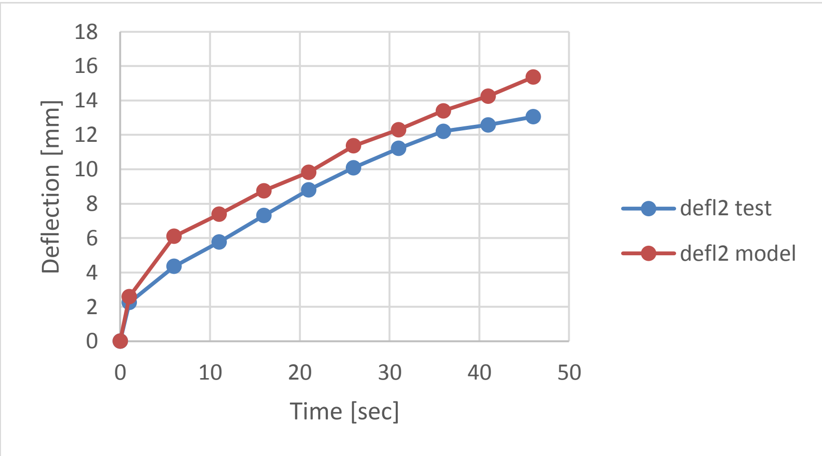
6.6 Results

The following graph shows the temperature data of thermocouple number six (TK6) during the test and in the model. Tk6 is installed in the middle of the pane, which is between two plate thermocouples number 2 and 4 (TOV2&4). The furnace temperature are measured by the plate thermocouples during the test. These plate thermocouples are installed under the pane A. These measured temperatures are used for making two separated models. As can be seen in the graph, the model with TOV2 results are closer to the results of the test. In the graph it is clear that the model shows higher temperature than the test. But the difference is not big.



Graph. 6.4 Temperature test and model results

The deflections results are illustrated in next graph. This data show that model deflection higher than test one. Because model temperature was also higher (pervious graph). Higher temperature results in more glass deflection.



Graph. 6.5 Deflection test and modek results

Following figure present stress at bottom side of pane A. This results show some tensile stresses around steel supports, where glass fracture is also occurred. This means model gives a correct estimation of fracture location. According to availed literature, maximum annealed glass stress capacity is around 45 Mpa. However this is a theoretical estimation and is not exact. DIANA model shows tensile stress is around 10 MPa after 45 seconds which is lower than theoretical estimation. This means model does not give an exact estimation about stress value. But it is also possible that theoretical estimation is very optimistic and just valid for room temperature. Moreover used glass properties for making model were also not exact data. Because no exact data for glass properties is available. This properties are discussed in chapter “Glass as a Material”.

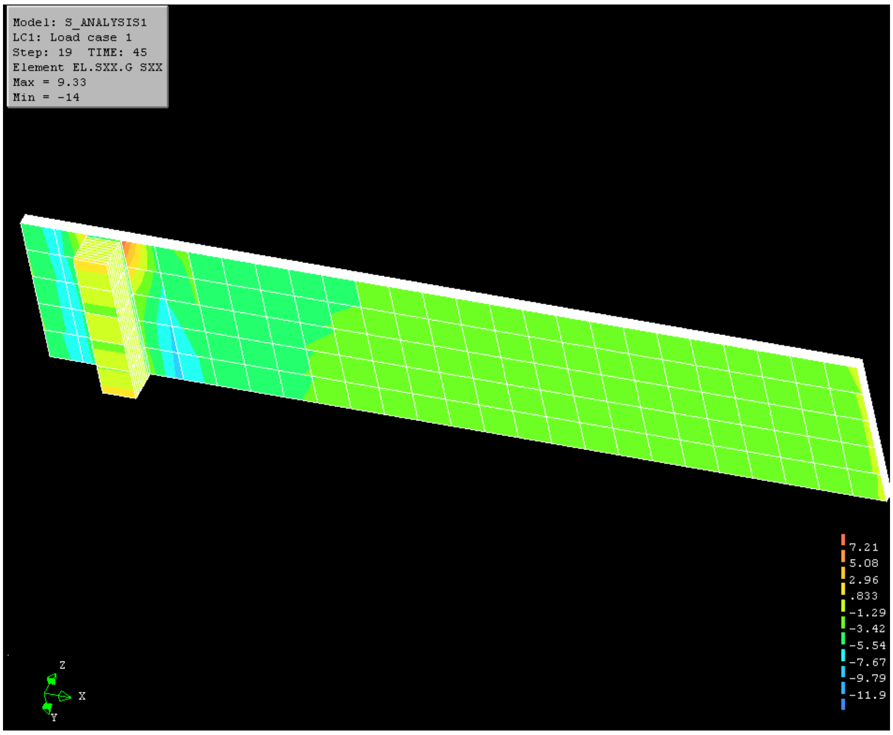


Figure 6.7 Stresses at the bottom side of the beam

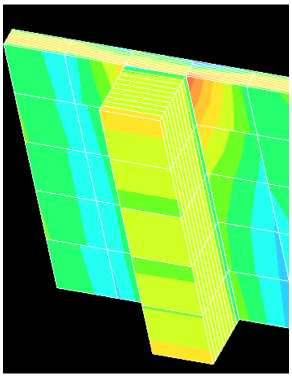
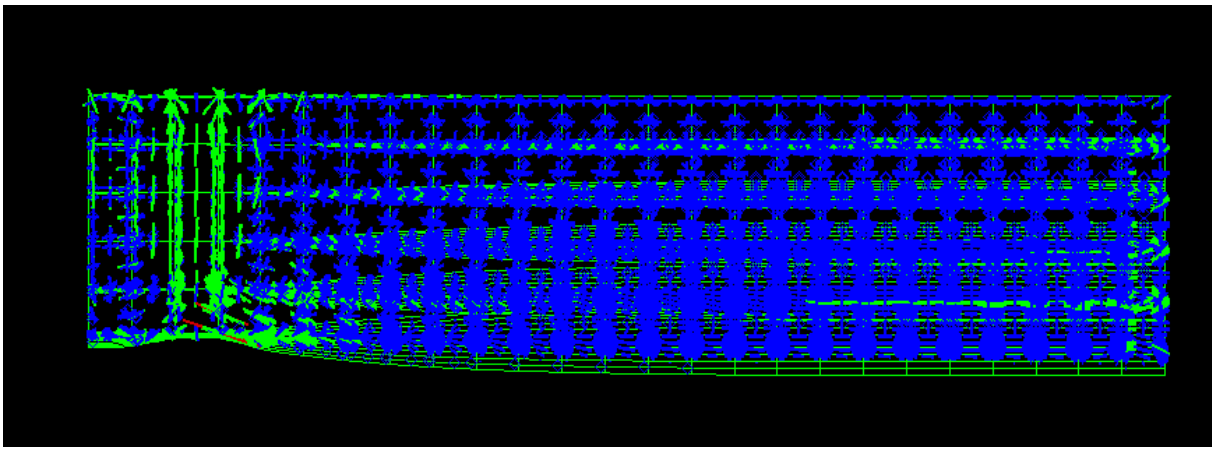


Figure 6.8 Tensile stress close to steel support

The following figure shows the top view of glass pane. As can been in the figure some tensile stresses are present (red dashed line) close to the steel support. Moreover it can been that the expansion is larger at the right side of steel support, because the glass is warmer at these areas. The warmer part of the glass tended to be expanded and the colder part (left side of the steel support) resisted this expantion. For this reason tensile stresses are occurred close to boundary line between warm and cold parts on the glass surface. Furthermore glass connection with steel makes this area more critical.



Graph. 6.6 Pane A expansion

7 Discussion

In this section the main objective will be evaluated to find out whether or not research questions have been satisfyingly answered.

Annealed Glass

None-structural and structural annealed glass were tested during the experiments series 1, 2 and 3. At the beginning of these tests the temperature gradient was high especially close to steel supports. For this reason annealed glass is broken around these supports very quickly (after 1-2 minutes). This seems to imply that annealed glass is very sensitive to the temperature differences on the glass surface.

Moreover, DIANA model shows tensile stress at these locations. In other words these temperature differences caused tensile stress at mentioned location. The warmer part of the glass tended to be expanded and the colder part resisted this expansion. That is why tensile stresses occur close to boundary lines between warm and cold parts on the glass surface. And the glass could not resist this stress and it failed.

As it was mentioned, location of the glass fracture was close to steel supports during these three tests, because steel and glass had different behavior during fire. Steel temperature was lower than the glass. This temperature difference plays also an important role in the thermal break phenomenon. A strip of Promatect isolation is used to test fully tempered and heat strengthened glass in order to limit the temperature difference between glass and steel. However, this was only a temporary solution for this research. In other words, joint details need extra attentions if glass needs to be used as a fire resistant structural element. Otherwise, glass fails at temperature 40-50 °C, which occurs during these experiment series.

Furthermore, annealed glass is tested horizontally and vertically during the experiment series 1 and 2. The results of these tests show that lying glass resisted longer than standing glass. The test results show that annealed glass performance was very weak at high temperatures due the thermal break. It means that annealed glass (without any improvement) does not have the capabilities to be used as a fire resistant structural element.

Fully Tempered Glass

None and structural fully tempered glass are tested during the experiments series 4. The fully tempered glass resisted longer (about 11 minutes) than annealed glass and did not break during these tests. However the glass behavior was critical when the glass temperature was increased to 550-600°C. The glass behavior changed to plastic phase at this temperature. Therefore the glass was not solid anymore and behaved more like liquid material. Afterwards, the glass was not able to carry any loads even the self-weight. The glass pre-stress is decreased during this period of time. And fully tempered glass changed to annealed when the glass pre-stress fell to zero. Then glass became sensitive to thermal break like previous tests (annealed glass). The test results show that fully tempered glass should be designed in such a way that the glass temperature stays lower than the critical temperature (550-600°C) for certain amount of time (30 minutes). In this way fully tempered glass has the capabilities to be used as fire resistant structural element. Two solutions are proposed for this improvement in the recommendations section.

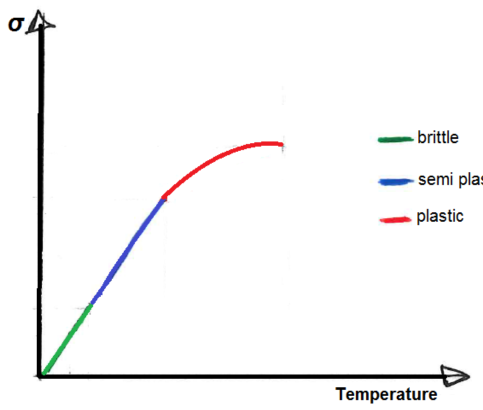
Heat strengthened glass

None and structural heat strengthened glass are tested during the experiments series 5 and 6. Results of the testing structural glass show that the loadbearing capacity of the glass decreased considerably when fire occurred. For this reason pane L was not able to carry 6% of the load that the glass carried at room temperature. This pane is broken in the middle part after 4.15 minutes while the glass temperature was 380°C. Moreover, heat strengthened glass behavior changed to plastic phase when the glass temperature reached 550-600°C. It means that this temperature is critical for both fully tempered and heat strengthened glass types. The test results show that the heat strengthened glass is minder suitable than fully tempered glass. For this reason this glass type needs more improvements and extra requirements in order to be able used as fire resistant structural element.

Figure 7.1 Fully tempered and heat strengthened glass after testing

Failure Category

The test results of annealed, fully tempered and heat strengthened glass show that the glass behavior at high temperatures can be divided in three failure categories; brittle, semi plastic and plastic failures. The failure of annealed glass belongs to first category; brittle failure. This glass type is failed very quickly at very low temperature (40-100°C). The fully tempered glass behavior changed to plastic phase at the critical temperature (550-600°C). Therefore the glass was not solid anymore and behaved like liquid material. This changing occurred without any break during the test. The heat strengthened glass deflected considerably when the glass reached the temperature of 400°C. This glass type behaved like solid-liquid material between 400 and 550°C. That is why this glass belongs to second category.



Graph. 7.1 Failure Category

DIANA Model

Various DIANA models were made during this research. Several thermal and mechanical properties were applied in these models. Most of these properties depend on temperature changing. Unfortunately not sufficient data is available about these glass properties. For this reason making a model in DIANA for glass fire behavior became very challenging. However, the models were made based on the available data which are explained in chapter "Glass as Material". And model results showed good agreement with the test results, which means the models gives a correct estimation of glass behavior at high temperatures. In order to be able to make a model with more precision, glass properties need to be determined. For this reason several material tests should be performed at the beginning of the next research.

Testing Method

Metal wires are used for the deflection measuring. The results show that these wires are extended considerably during the performed tests. This means that measured glass deflections are not exact and reliable. Deflection should be measured directly from deflected glass element, and using instruments such as metal wire will not lead to correct results. Metal wire has lower weight than glass. That is why the wire is heated faster. Moreover, metal wire has high heat conductivity. This results in quick wire extension while glass is not really heated yet. A new measuring method should be determined in order make measuring glass deflection directly (without any instrument like wire) possible.

The thermocouples and the mantel-couples measured the glass surface temperatures for testing at the furnace and in the furnace respectively. Test results show that the glass temperature is increased slower than the furnace temperature. This temperature difference was present for about 10 minutes. The thermocouples and the mantel-couples are pasted on the glass surface by using glue. This glue may cause some isolation around the thermocouples and the mantel-couples. That is why these recorded glass temperatures is lower than the furnace temperature. New measuring method should be determined in order make temperature measuring with more precision possible. For example thermocouples can be placed between layers of laminated glass during glass production.

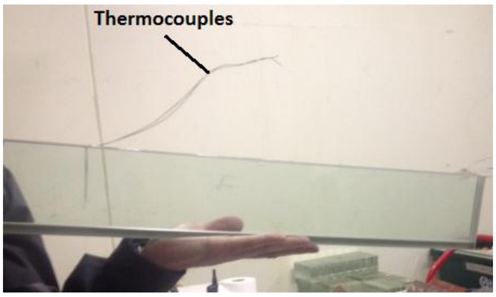


Figure 7.2 Laminated glass with inside thermocouples (Source: Dr. Louter beams)

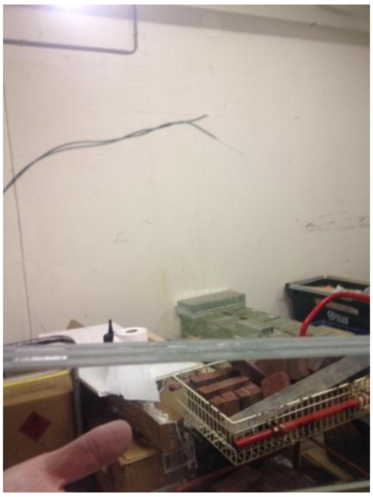


Figure 7.3 Thermocouples inside the glass (Source: Dr. Louter beams)

Single glass layer is tested during all the experiments series. The results show that one layer was not sufficient. This means that using laminated glass is essential in order to have enough fire resistance (30 minutes).

8 Overall Conclusions and Recommendations

In this section it will be evaluated whether the main objective and sufficient answers for research questions have been satisfied. Moreover the recommendations for further research regarding the testing and the designing are elaborated in this chapter.

8.1 Conclusions

- The sensitivity analysis showed that from the material properties used as input for DIANA models, the heat specific property has the most influence on the glass temperature.

- Through the data analysis and the observations of the experiments series 1, 2 and 3 can be concluded, annealed glass was very sensitive to thermal break caused by the temperature differences around 70°C on the glass surface. Moreover the maximum temperature on the glass surface was around 100°C when the glass broke. The average temperature of the furnace was around 458 °C at this moment (glass failure).

- Based on the different behavior of steel and glass at the high temperature, can be noted that the thermal break phenomenon is occurred at the joint locations (connection between glass and steel support). For this reason joint details need extra attentions if glass needs to be used as a fire resistant structural element.

- Annealed glass performance was very weak at high temperatures due the thermal break phenomenon. It seems to imply that annealed glass (without any improvement) does not have the capabilities to be used as a fire resistant structural element.

- From the analysis results presented experiments series 1 and 2 became obvious lying glass resisted longer than standing glass, which is according to expectation from room temperature static tests.

- Through the data analysis and the observations of the experiments series 4, 5 and 6 can be concluded that 550-600°C is the critical temperature for both fully tempered and heat strengthened glass types. The average furnace temperature was around 615°C when glass temperature reached the critical temperature (550°C).

- The glass behavior changed to plastic phase at the critical temperature. Subsequently the glass was not solid anymore and behaved more like liquid material. Afterwards the glass was not able to carry any loads, even not the self-weight.

- The test results experiments series 4, 5 and 6 show that heat strengthened glass is less suitable than fully tempered glass.

- Based on the observations, the glass behavior at high temperatures can be divided in three failure categories; brittle, semi plastic and plastic failures.

- Fully tempered glass should be designed in such way that the glass temperature stay lower than the critical temperature (550-600°C) for certain amount of time (30 minutes). In this way fully tempered has the capabilities to be used as fire resistance structural elements. It should be mentioned that the relation between maximum allowable tensile stress and temperature, need to be determined first. This information is essential in order to determine if fully tempered glass can be used as fire resistant element.

- Using laminated glass is essential in order to have sufficient fire resistance (30 minutes). The interlayers and the outside glass layers can keep the temperature of the middle layer(s) (loadbearing part) below the critical temperature for certain amount of time.

- Several thermal and mechanical properties were applied in the DIANA models. Most of these properties depend on temperature changing. The model results showed good agreement with the test results, which means the models gives a correct estimation of glass behavior at high temperatures.

- Through the data analysis and the observations of test series 1 to 6 seems to imply that fully tempered glass, with some improvements, has the capabilities to be used as a structural material under fire loads. Two solutions are proposed for this improvements in the recommendations section. However the relation between maximum allowable tensile stress and temperature, need to be determined first. This information is essential in order to determine if fully tempered glass can be used as fire resistant element.

8.2 Recommendations

- A new measuring method should be determined in order make measuring glass deflection directly (without any instrument like metal wire) possible. For example laser can be an option in order to have no physical connection between measurement equipment and glass. However the transparency of glass makes this method also risky. A disc should be placed at the measuring point, in order to prevent that the laser goes through the glass surface and measures the floor of the furnace.

- A new measuring method should be determined in order make temperature measuring with more precision possible. For instance thermocouples can be placed between layers of laminated glass during the glass production. Moreover infrared thermometer can be another option for temperature measuring.

- Laminated glass designing needs the following requirements:

  - Middle layer(s) needs to be designed as the loadbearing part. This means the middle layer(s) needs sufficient thickness and characteristics.
  - Temperature of the middle layer(s) should not be higher than 300°C (200°C lower than the critical temperature).
  - Other layers should protect the middle layer(s) so that it stays lower that the critical temperature.

- Available methods for non-structural fire resistant glass can be used as a reference for making a design for structural element. For instance using transparent intumescent coating could be an option in this field.

- It should be mentioned that the bottom side of the middle layer(s) in a laminated glass is critical (Figure 8.1.a), because other layers protect the right and left sides of middle layer(s). But the bottom side is still in direct contact with fire. Two proposals can be made in order to solve this problem:

  - The loadbearing glass (inside glass layer) can be protected by placing four glass layers (outside layers) around it. In this way the inside glass layer(s) can stay longer below the critical temperature (Figure 8.1.b).
  - Using reinforced glass can be proposed as a second option. The reinforcement should be placed under the middle layer in order to protect this layer from early heating. The inside of the reinforcement can be filled with gel material. This gel can be used for more moisture absorption and will help the middle glass to stayed cooler for a longer time. This steel part works more like a temperature “blocker” than a real reinforcement. However it is also possible to be designed for both functions (Figure 8.1.c)

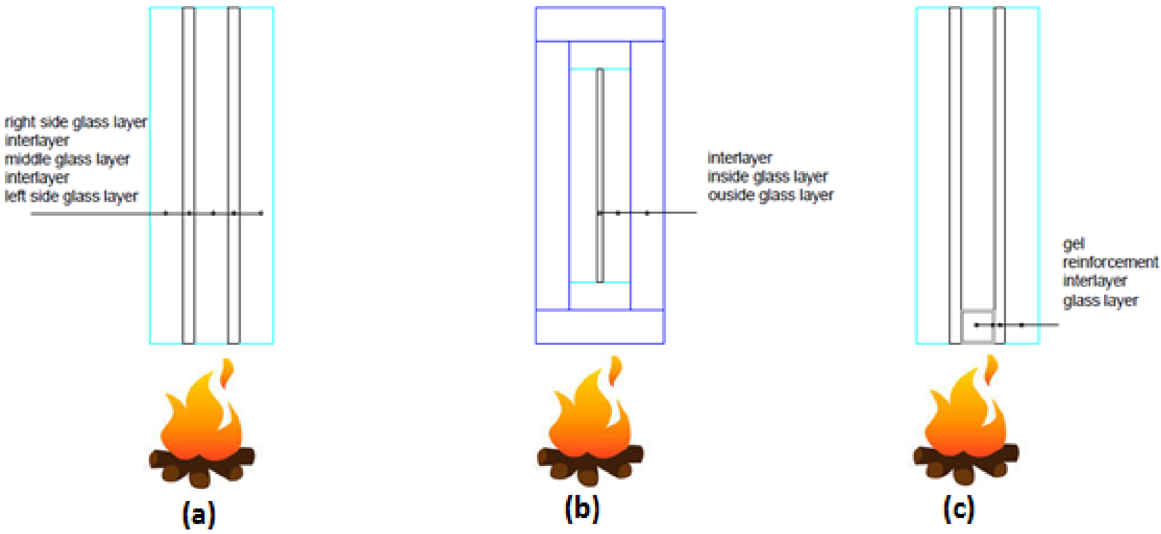


Figure 8.1 Proposals for laminated glass designing

- In order to be able to make a model with more precision, glass properties need to be determined. For this reason several material tests should be performed at the beginning of the next research.

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- http://www.joostdevree.nl/shtmls/warmtecapaciteit.shtml
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- www.detail-online.com
- www.designboom.com
- https://johnvagabondscience.wordpress.com
- www.bbc.co.uk
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- http://community.ceramicartsdaily.org/
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List of The Recorded Video's

1. **Experiment Series 1; annealed panes A & B**
2. **Experiment Series 2; annealed panes D***
3. **Experiment Series 3; annealed panes J & K**
4. **Experiment Series 4; fully Tempered panes N & O**
5. **Experiment Series 5; heat strengthened pane L**
6. **Experiment Series 6; heat strengthened pane M**

*The Pane E is not visible in the video

List of Figures

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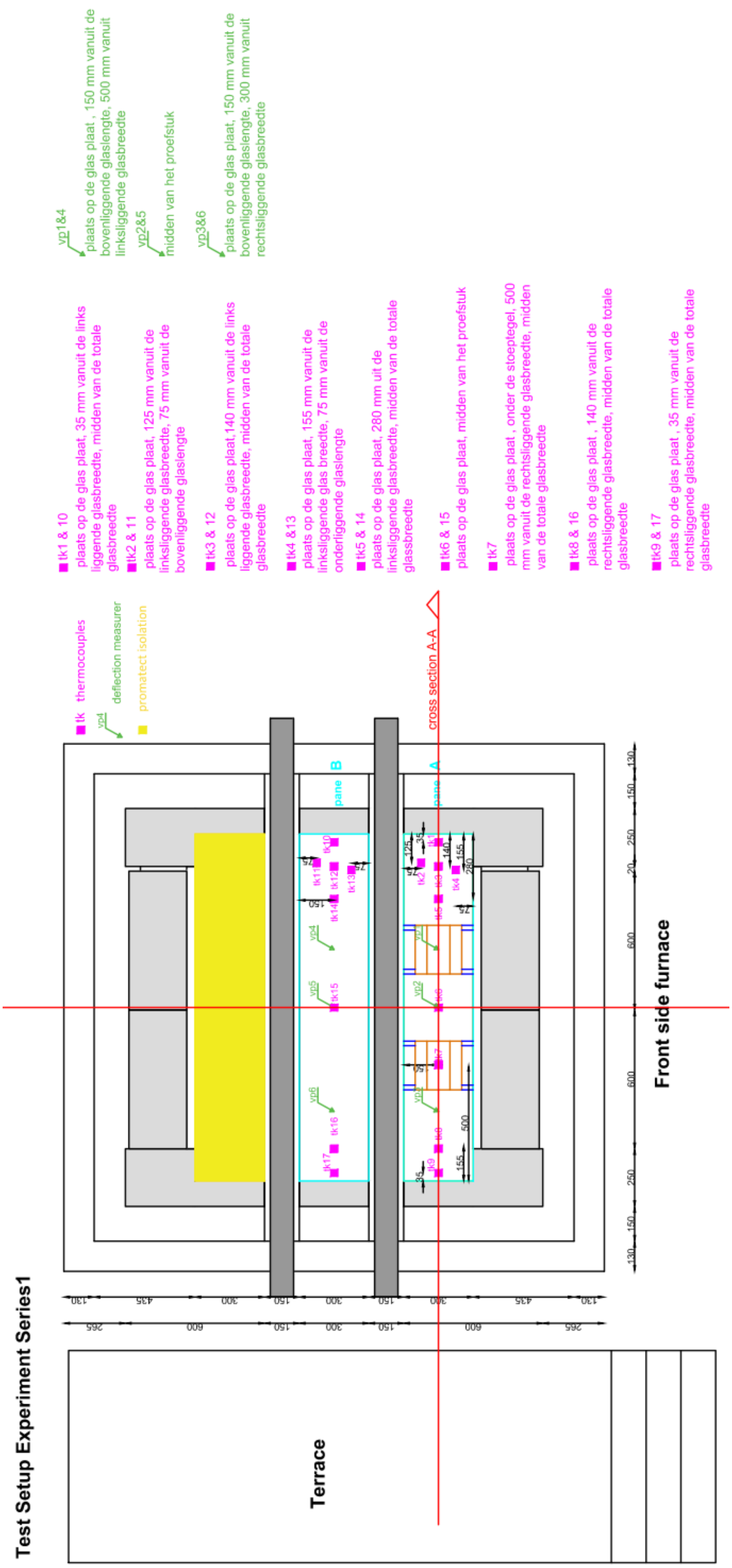
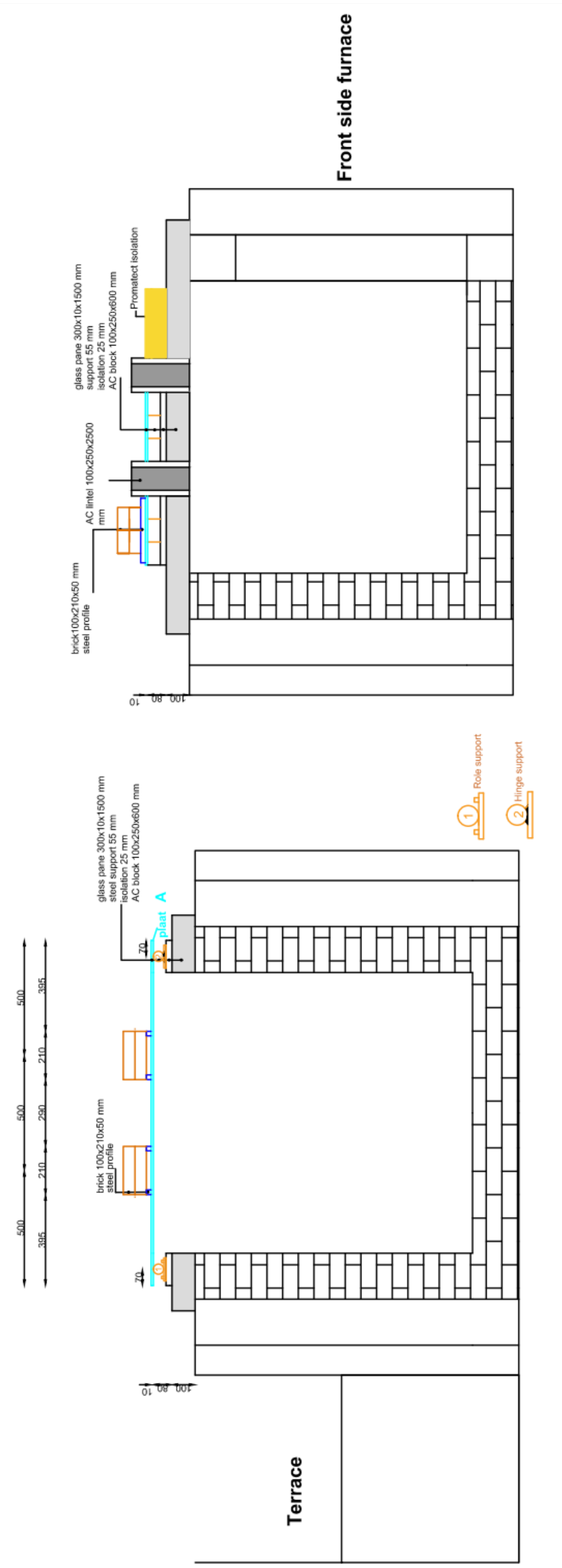
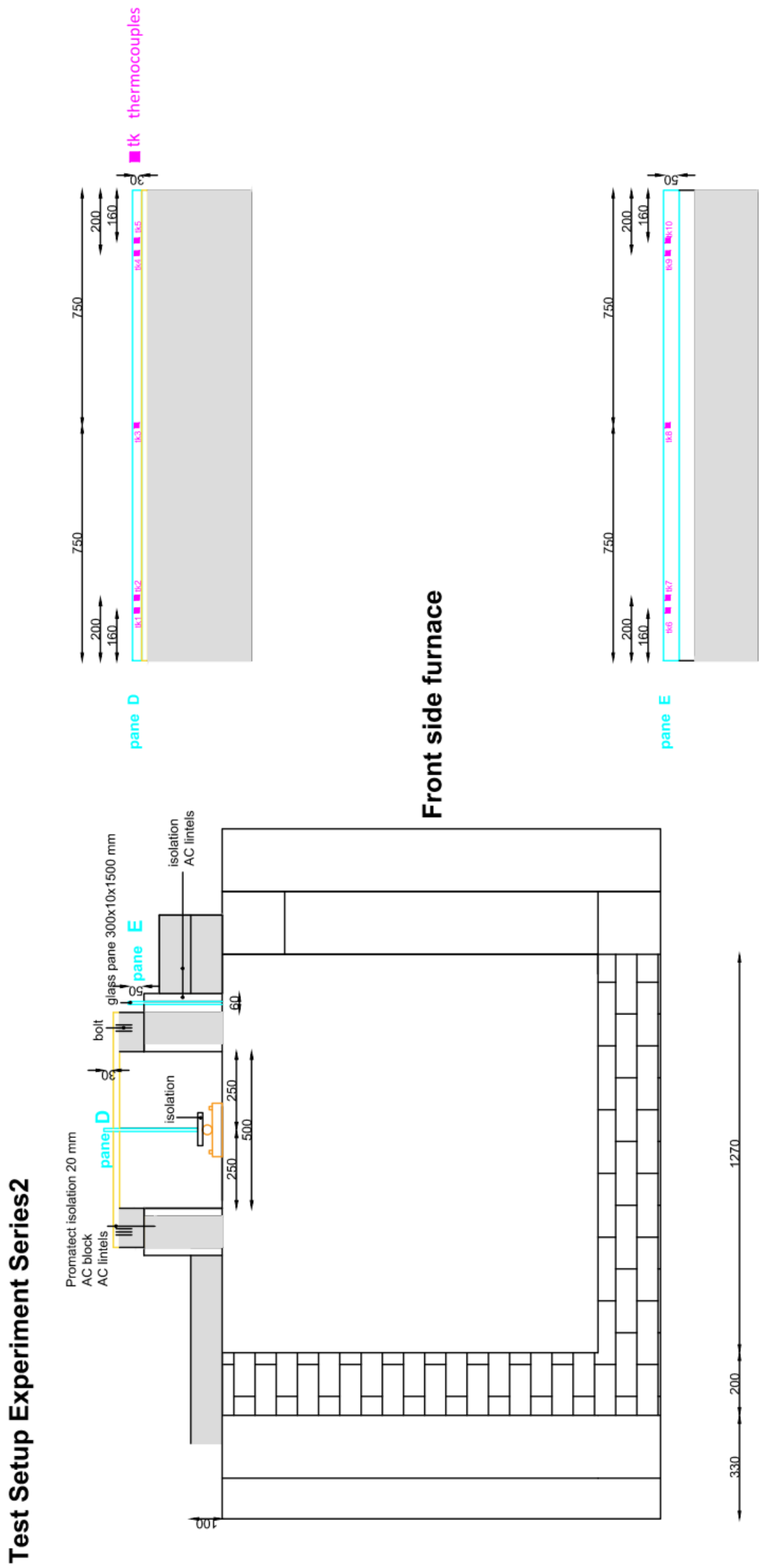
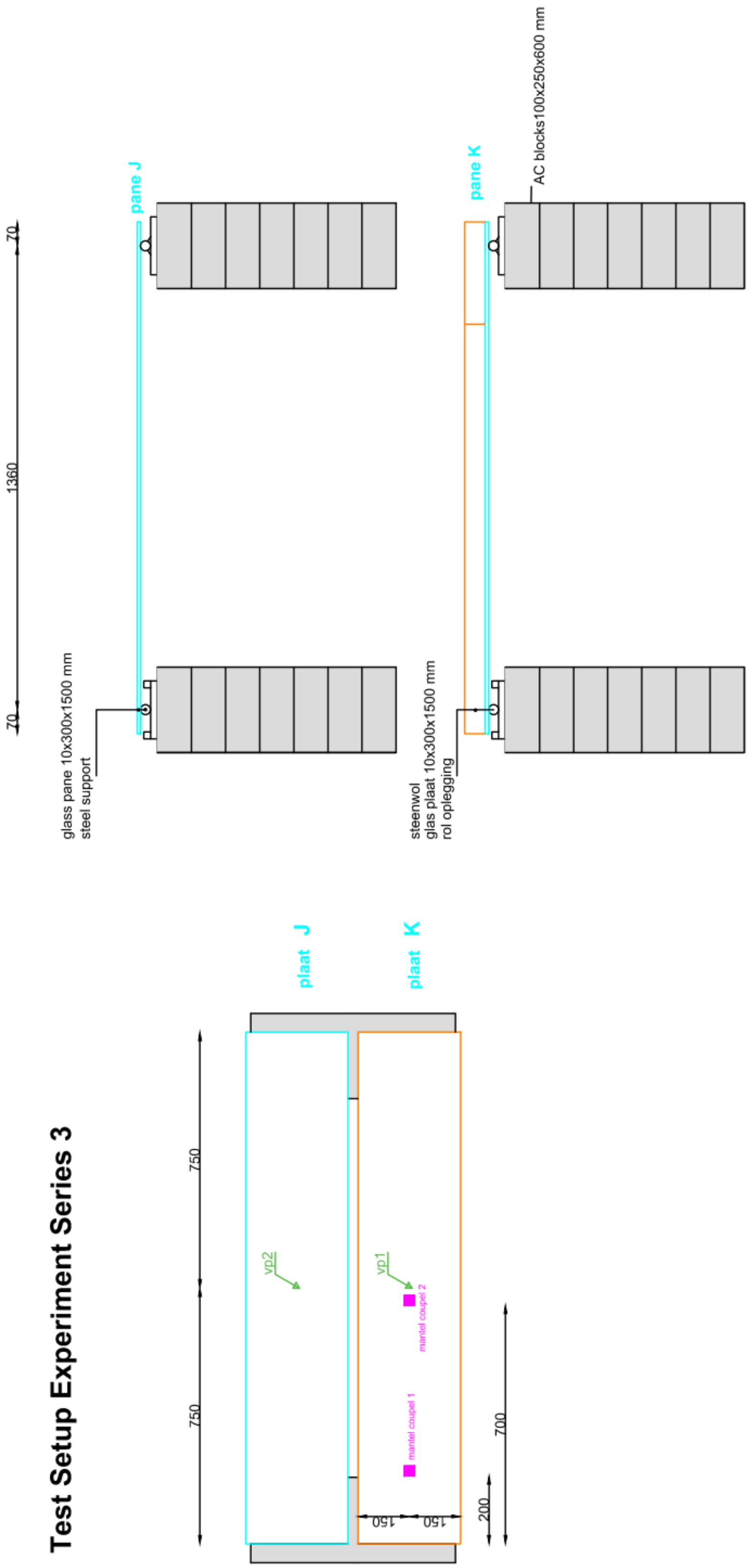
Appendix 1 Efectis Setup Drawings

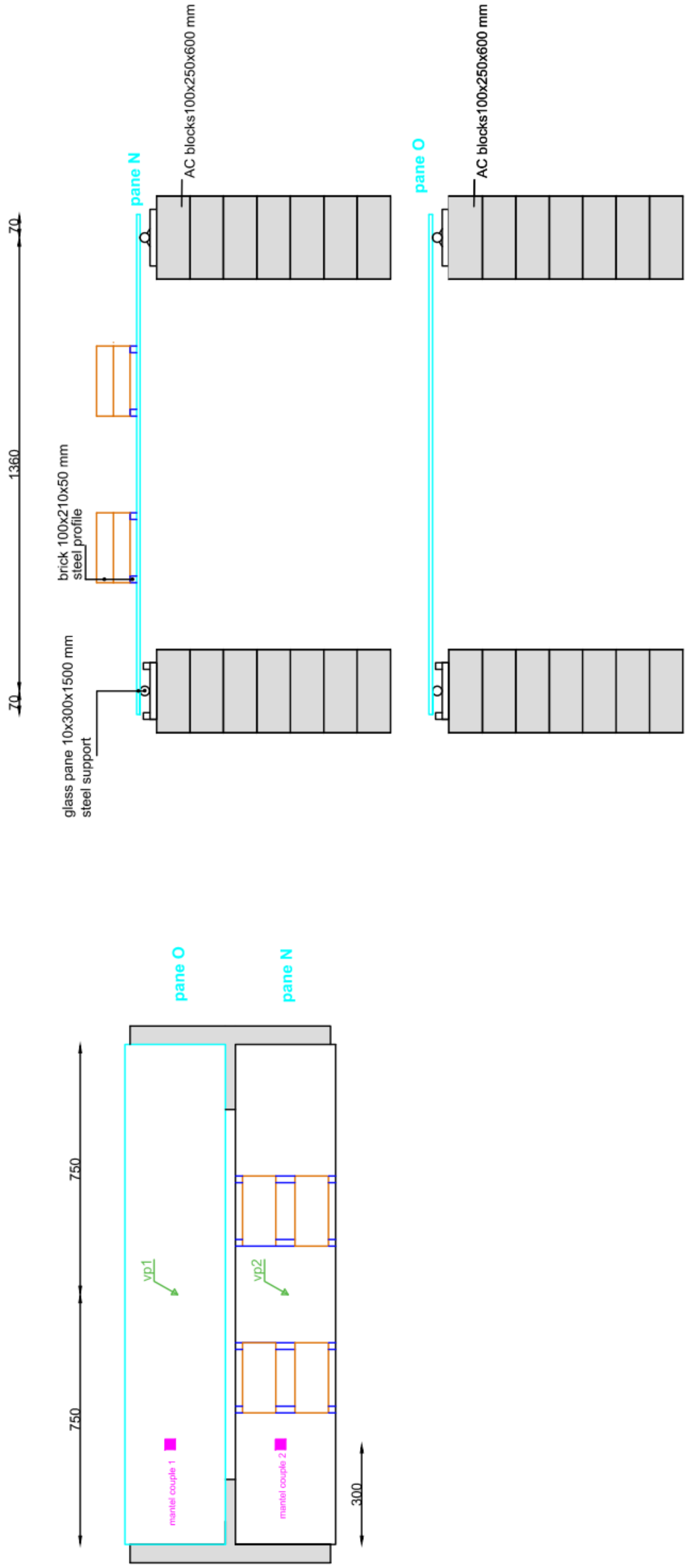

Test Setup Experiment Series1
Terrace
Front side furnace
pane B
pane A
cross section A-A
tk thermocouples
vp4 deflection measurer
promatect isolation
tk1 & 10
plaats op de glas plaat, 35 mm vanuit de links liggende glasbreedte, midden van de totale glasbreedte
tk2 & 11
plaats op de glas plaat, 125 mm vanuit de linksliggende glasbreedte, 75 mm vanuit de bovenliggende glaslengte
tk3 & 12
plaats op de glas plaat,140 mm vanuit de links liggende glasbreedte, midden van de totale glasbreedte
tk4 &13
plaats op de glas plaat, 155 mm vanuit de linksliggende glas breedte, 75 mm vanuit de onderliggende glaslengte
tk5 & 14
plaats op de glas plaat, 280 mm uit de linksliggende glasbreedte, midden van de totale glassbreedte
tk6 & 15
plaats op de glas plaat, midden van het proefstuk
tk7
plaats op de glas plaat , onder de stoeptegel, 500 mm vanuit de rechtsliggende glasbreedte, midden van de totale glasbreedte
tk8 & 16
plaats op de glas plaat , 140 mm vanuit de rechtsliggende glasbreedte, midden van de totale glasbreedte
tk9 & 17
plaats op de glas plaat , 35 mm vanuit de rechtsliggende glasbreedte, midden van de totale glasbreedte
vp1&4
plaats op de glas plaat , 150 mm vanuit de bovenliggende glaslengte, 500 mm vanuit linksliggende glasbreedte
vp2&5
midden van het proefstuk
vp3&6
plaats op de glas plaat, 150 mm vanuit de bovenliggende glaslengte, 300 mm vanuit rechtsliggende glasbreedte

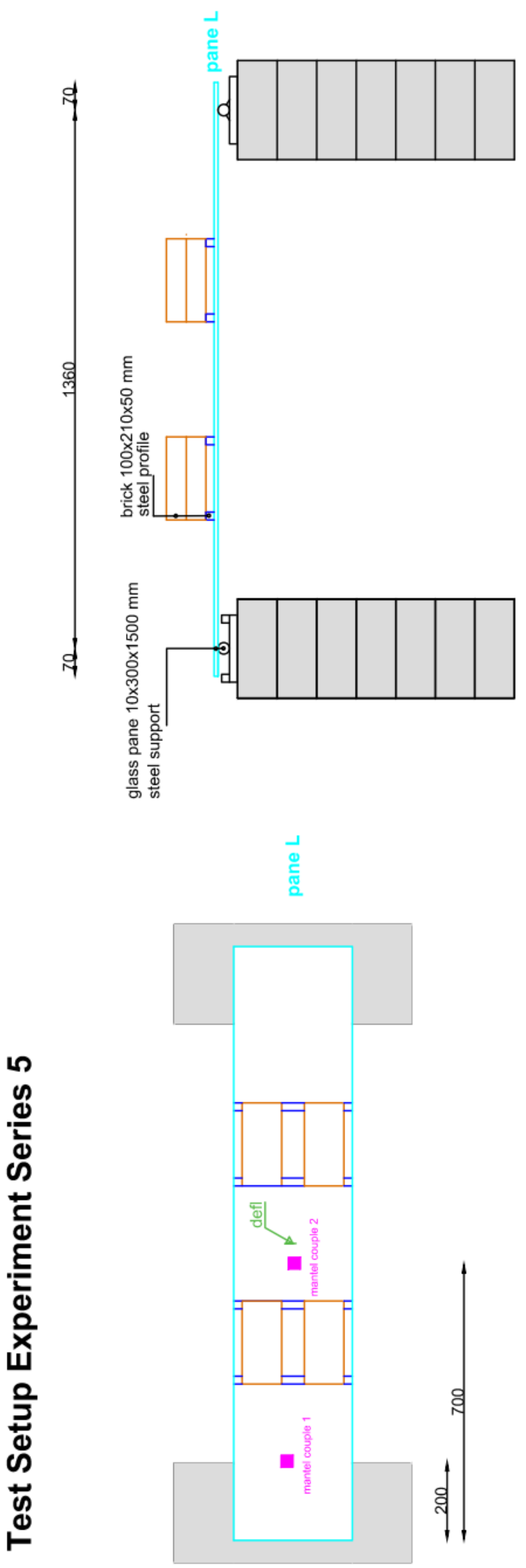

Front side furnace
glass pane 300x10x1500 mm
support 55 mm
isolation 25 mm
AC block 100x250x600 mm
Promatect isolation
AC lintel 100x250x2500 mm
brick100x210x50 mm
steel profile
Role support
Hinge support
glass pane 300x10x1500 mm
steel support 55 mm
isolation 25 mm
AC block 100x250x600 mm
plaat
A
brick 100x210x50 mm
steel profile
Terrace


Test Setup Experiment Series2
Front side furnace
tk thermocouples
pane D
pane E
Promatect isolation 20 mm
AC block
AC lintels
isolation
bolt
glass pane 300x10x1500 mm
isolation
AC lintels
1270
200
330
100

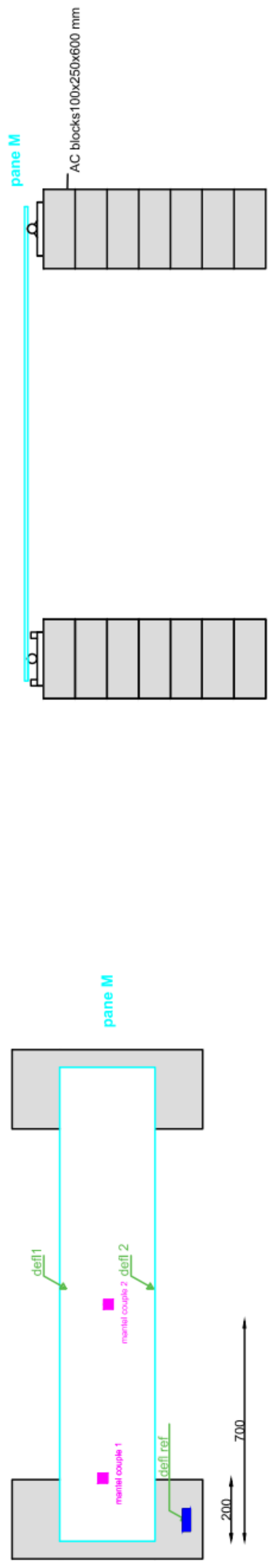

Test Setup Experiment Series 3
70
1360
70
glass pane 10x300x1500 mm
steel support
pane J
steenwol
glas plaat 10x300x1500 mm
rol oplegging
pane K
AC blocks100x250x600 mm
750
750
plaat J
plaat K
vp2
vp1
mantel coupel 1
mantel coupel 2
150
150
200
700

Test Setup Experiment Series 4




Test Setup Experiment Series 5
pane L
70
1360
70
brick 100x210x50 mm
steel profile
glass pane 10x300x1500 mm
steel support
pane L
defl
mantel couple 2
mantel couple 1
700
200

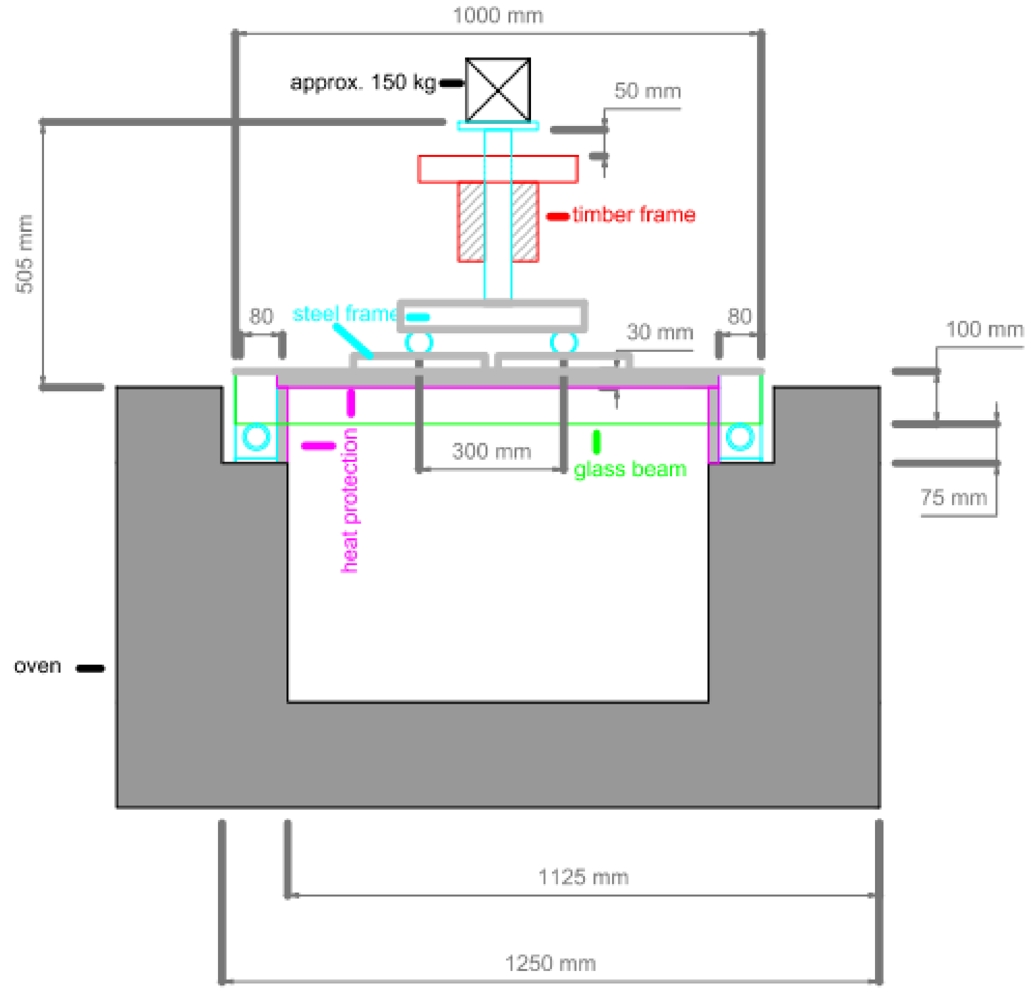
Test Setup Experiment Series 6



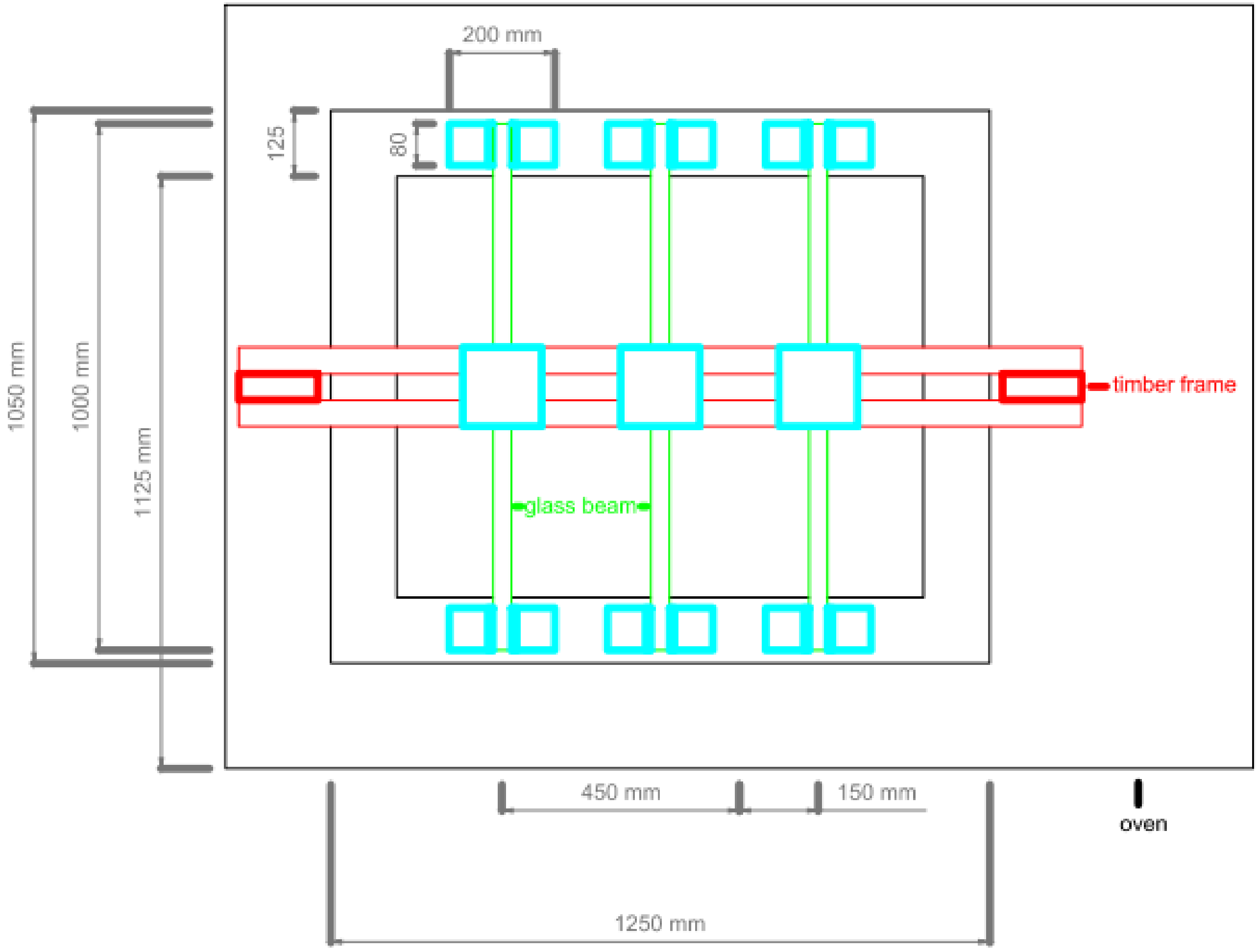
Appendix 2 Empa Setup Drawings

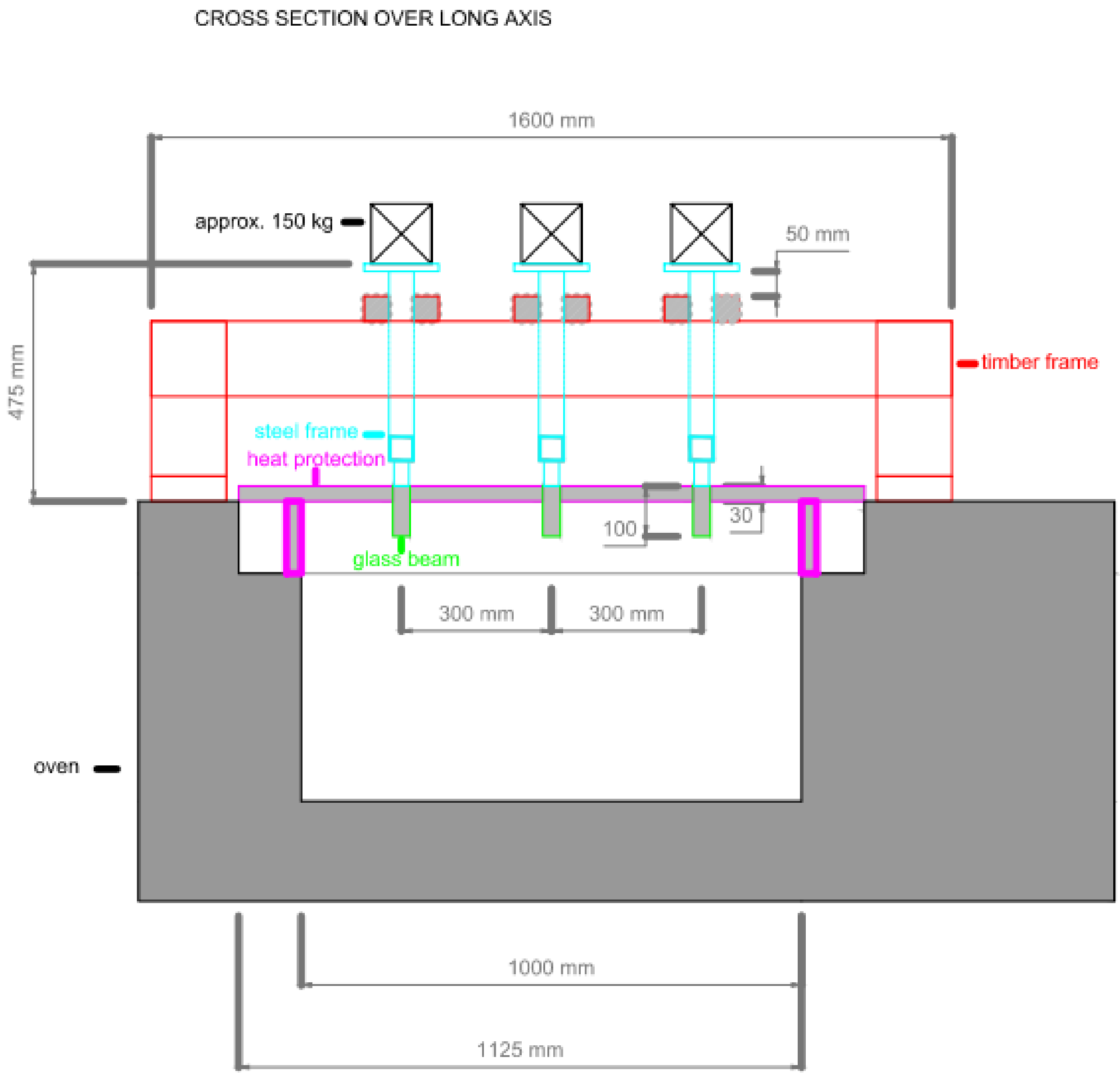
Source: Dr. Louter tests documents

CROSS SECTION OVER SHORT AXIS



TOP VIEW OF TEST SETUP




CROSS SECTION OVER LONG AXIS
1600 mm
approx. 150 kg
50 mm
475 mm
timber frame
steel frame
heat protection
100
30
glass beam
300 mm
300 mm
oven
1000 mm
1125 mm

Appendix 3 Material Properties

Soda Lime Silica Float Glass

Temperature Independent Properties

Modulus of Elasticity (Young's)	10.4 x 10 ^{6} psi (72 GPa)
Modulus of Rigidity (Shear)	4.3 x 10 ^{6} psi (30 GPa)
Bulk Modulus	6.2 x 10 ^{6} psi (43 GPa)
Poisson's Ratio	0.23
Density	156 lb/ft^3 (2500 kg/m^3)
Coefficient of Thermal Stress	50 psi/°F (0.62 MPa/°C)
Thermal Conductivity at 75°F	6.5 Btu.in/hr.°F.ft^2 (0.937 W.m/m^2.°C)
Coefficient of Linear Expansion (75-575 .°F)	4.6 x 10 -6 in/in.°F (8.3 x10 -6 mm/mm.°C)
Hardness (Moh's Scale)	5-6

Temperature Dependent Properties

Temperature[°C]	Modulus of Elasticity (Young's)
0	7.26E+04
114	7.17E+04
200	7.07E+04
286	6.98E+04
400	6.85E+04
457	6.76E+04
514	6.57E+04
600	6.16E+04
720	5.30E+04
800	6.89E+01
850	6.89E+00
900	6.89E-02
950	1.89E-03

Temperature[°C]	Thermal Conductivity without radiation [W/m°C]
29	1.1
100	1.14
200	1.16
300	1.2
350	1.25
400	1.23
500	1.25
550	1.23
700	1.23
800	1.21
900	1.24

Temperature [°C]	Thermal Conductivity radiation [W/m°C]
0	1.1
400	1.2
500	1.4
600	1.6
700	1.8
800	2.1
900	2.4

9.1.1.1

Temperature[°C]	Specific Heat [J/mol K]
73	54,7
101	57,2
128	59,4
153	61,1
178	62,8
202	64
225	65,3
248	66,4
271	67,5
293	68,4
315	69,2
336	69,9
358	70,7
379	71,3
400	71,6
421	71,9
431	72,2
442	72,8
452	73,7
462	76
473	80,3
483	88,2
493	92,3
503	89,7
514	80
524	80
534	79,2
554	78,7
573	78,9
593	79,4
613	80,2
632	81
652	81,4

671	82
690	82,2
709	82,9
728	83,4
746	83,8
766	84
784	84,1
802	84,6

Sentry Glass Interlayer

Temperature Dependent Properties

Modulus of Elasticity (Young's)	3.0E+02
Poisson's Ratio	4.65E-01
Density	9.5E-07
Thermal Conductivity	2.46E-04
Heat Specific	2.0E-04

Temperature Independent Properties

Temperature[°C]	E
10	597
20	493
30	416
40	178
50	27.8
60	12.6
70	5.1
80	2.52
100	1.5
400	0.05
500	0.005
700	0.00001
920	0.000001

Steel

Temperature Independent Properties

Modulus of Elasticity (Young's)	2.1 x 10^{-20} *
Poisson's Ratio	0.30
Density	2.1 x 10^{-6}

*Steel supports have only thermal effect on glass during the test. For this reason a very low E modulus is used for making models.

Temperature Dependent Properties

Thermal Conductivity	[W/mk]
20	53,334
30	53,001
100	50,67
200	47,34
300	44,01
400	40,68
550	37,35
600	35,685
650	34,02
700	32,355
720	30,69
735	30,024
800	29,5245
900	27,36

Heat Specific	[J/kgK]
20	439,8018
30	446,7289
100	487,62
200	529,76
300	564,74
400	605,88
500	666,5
550	708,2775
600	760,2174
650	813,75
700	1008,158
720	1388,333
735	5000
800	803,2609
900	650