Fire Resistant Structural Glass Beams

Developing design recommendations for future development and fire certification of structural glass beams

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P5 Master thesis
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I will start with my graduation committee.

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Contents

Introduction

Glass is a common product that everybody uses or comes in contact with on a daily basis. When grabbing a glass of tap water and looking outside to see what the weather is today. Almost every building today uses glass in some form or manner, as window glass, as whole facades, roofs or as a decorative item. On the worldwide market, the production of flat glass has a yearly revenue of approximately 90 billion euro's according to Glass Magazine, with a market share of 15 billion euro's in western Europe.

Glass is a building material that has been around for centuries. Fragments have been found of window glass dating back to the Vesuvius outbreak in 79 AD during the roman era. Since the very first structures, daylight penetration has been of great importance. The invention of cast glass window panes enabled builders to create openings without letting rain and wind enter(Schittich, Balkow, Schuler, & Sobek, 2007). This became the start of a long tradition of glass as one of the main components in the building industry and modern-day construction.

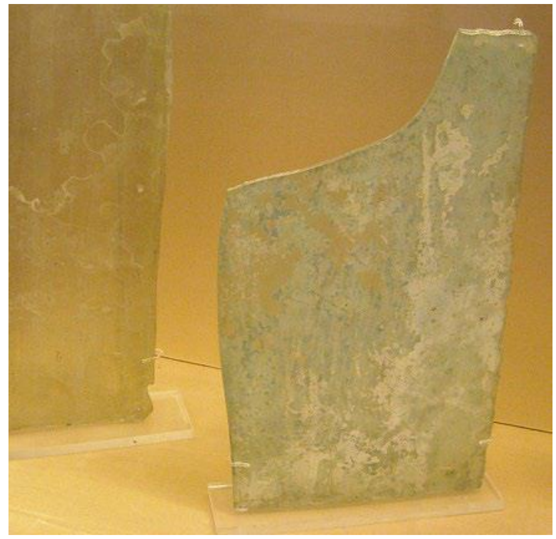


Figure 1 – Cast glass window fragments, 79 AD Pompeii
Source: https://www.flickr.com/photos/70125105@

Creating openings while closing of the building envelope is a property that describe the significance of glass. Glass is a material with a very high transparency, allowing people to look straight through the material. Jan Wurm(Wurm, 2007) describes the goal of using glass as "The greatest possible dematerialisation of the building skin" for architects and designers. The dematerialisation tries to create a safe and sheltered environment while maintaining a direct relation with the outside world.

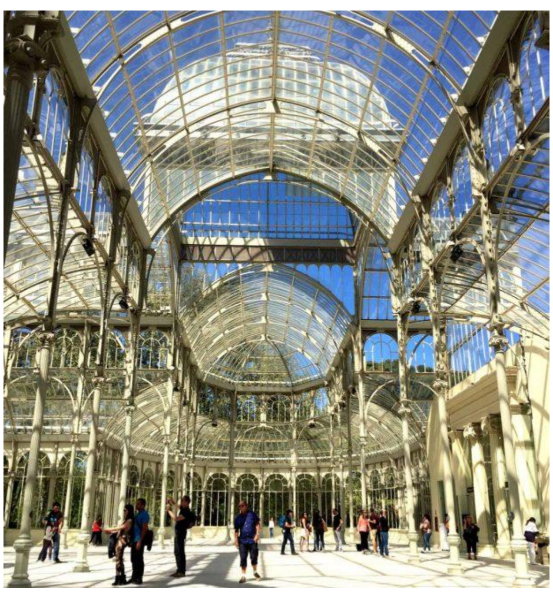


Figure 2 – Crystal Palace – Madrid
Source: https://i0.wp.com/theweekendguide.com/wp-content/uploads/2017/07/crystal-palace-madrid-e1507126389143.jpg?w=619&h=825&crop

During and in result of the English industrial revolution the demand for glass in buildings increased. Architects design buildings built completely of cast iron and glass panes. The most famous of these buildings is perhaps the Crystal Palace, which was designed and built to house The Great Exhibition of 1851. The 92.000 m^2 exhibition building was built using a cast iron structure which was filled in with sheet glass. Another example is the likely named Crystal Palace in Madrid of 1887.

From the inside of the building the visitor is in direct contact with the surrounding Buen Retiro Park in the city of Madrid. A picture from the inside can be seen in figure 2 The use of the glass creates a high daylight transmittance.

Dematerialisation of the structure

The dematerialisation as Jan Wurm described it has far from stopped. Architects and glass manufacturing companies have been expanding the boundaries of what is possible using glass. The technology of the production methods of glass continues to evolve. The production size of glass panels has been increasing according to the demand. Architects and building engineers are taking this a step further by attempting to dematerialise the construction by implementing transparent structural glass beams or columns in buildings.

Commissioned by Apple Retail, Eckersley O'Callaghan architects and engineers designed and built a fully transparent glass cube in a public square in Manhattan, New York. In 2005, the glass cube was built completely from glass and a few steel connectors. The completely transparent building attracted a lot of spectators and visitors. After a few years the production process had advanced and larger glass sheets could be produced. The client requested to replace the façade panels with larger panels of 3m x 10 meters.Glass façade with reinforcing ribs of laminated glass. The refurbished cube, as can be seen in the image below, was revealed in 2011.
Apple identifies itself with ground-breaking, technologically innovating concepts. Structural glass can be seen as a technological innovation in the building industry. The building of loadbearing structures that can be completely transparent has something mystical and fascinating about it.

Figure 3 – Fully transparent glass structure and façade – Apple Cube – Manhattan, New York
Source: Photographed by Peter Aaron

Glass has proved its potential as a structural building material, although the material has not been around for that long. Not when we compare glass to more common building materials such as wood, steel and concrete which have been used for a far longer period.

The properties of glass are very similar to concrete. Both materials can withstand large compressive loading, which can be very beneficial in a structural manner. On the other hand, the two materials are rather weak in tensile forces in the material leading to fractures. Due to its brittle nature, without the use of a form of reinforcement structural glass could fail without warning. In structural glass the glass is laminated with polymer interlayers to ensure a redundancy in the construction.

Relevance

Currently a lot of research is done into the performance of structural glass. Research which can results in innovating projects such as the example of the Apple Cube. This is accompanied by a growing demand from architects and designers to apply glass as structural material. It is not only the specialised firms that work with the material, structural glass can be applied in a broad range of applications and is seen more and more. However, there are limitations to the application of structural glass.

Where structural glass is applied in some projects, the use of the material is limited by current building regulations. Structural glass and glass in itself do not handle well under heat and fire loading. Therefore, structural glass may *not* be applied in applications that demand a form of fire resistance. If glass is to become a more common structural material, it has to live up to current regulations.

In a conversation with James O'Callaghan from Eckersley O'Callaghan the question was raised if there is demand for structural glass to be applied as a fire-resistant building element. He stated that as an architect his clients request building designs that demand building components with a certain fire rating.

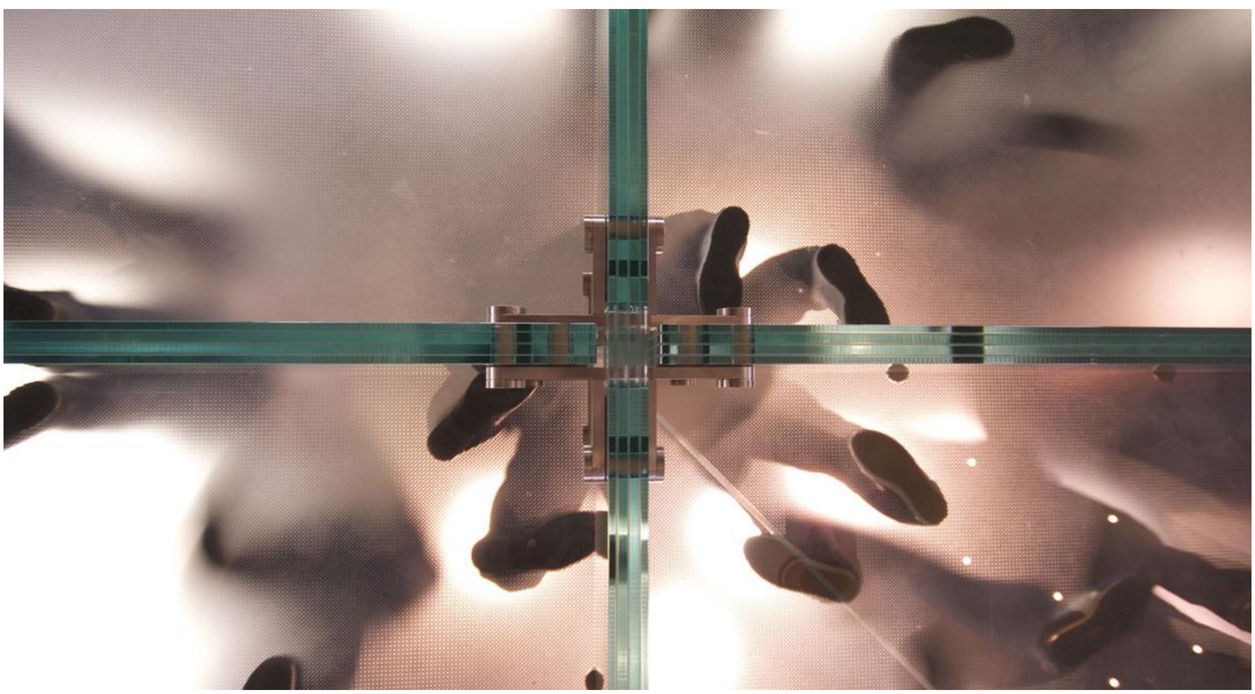


Figure 4 - Translucent structural glass landing - Apple store – Louvre, Paris
Source: Eckersley O'Callaghan –www.eocengineers.com/img/image_large/1298/APPLE_LOUVRE_LARGE_03.jpg

These requests now have to be turned down since structural glass components are currently unable to provide the fire resistance demanded by building regulations.

For structural glass to become as common as steel or concrete it will have to comply with more than just structural requirements. Building regulation states that multi storey buildings require a minimal fire resistance from their building components. According to researchers such as Debuyser, Louter and Bedon(Debuyser et al., 2017; Bedon, 2017; Debuyser et al., 2017; C. Louter & Nussbaumer, 2016), relatively little research has been conducted into the response of structural glass beams under fire loading.

During this graduation thesis, the aim is to create a better understanding of the behaviour of structural glass under fire loading and the overall requirements regarding fire safety and fire resistance of structural elements, in particular structural laminated glass beams.

So far, the master program has dealt with fire safety regarding emergency routing. During the MSc 2 project of Extreme focus was on the internal routing of large crowds of people in a public building. However, determining, simulating or in-depth knowledge regarding fire resistance of building materials and the effect on structural design has been out of the scope during the curriculum of the master track.

Problem statement

The aesthetics of structural glass and the innovative projects in which it is applied lends itself for development within the building technology track. In a lot of cases fire resistance in constructions is solved using conventional methods such as wrapping the constructive element in fire protective materials. Glass demands for a more strategic approach due to is transparent nature, simply covering the element in an insulating material nullifies the reason to use glass.

The approach to fire resistant glass ask for a technical design mentality in combination with the ability to develop a broad range of concepts that can be evaluated. In this graduation thesis design concepts of structural glass beams will be developed. These concepts will be tested to determine if they are able to withstand the high temperatures under fire loading for a significant period of time. According to Dutch building regulations the minimal resistance required would be at least 30 minutes.

The dilemma between showing the structural glass and protecting the construction in case of fire is one of the aspects that should be dealt with. Furthermore, currently extensive research has not yet been done into the performance of glass and structural glass in heat and fire loading situations and lastly no specific building regulations have been drafted to test structural glass elements.

Research questions

This graduation research will develop design recommendations for structural glass laminated beams. The glass beams should offer a minimal fire resistance as prescribed by building regulations while maintaining the natural transparency of glass.

The main research question of this graduation research is as following:

"In what way can a laminated structural glass beam be detailed, so that it maintains the aesthetic transparency of glass while being able to withstand fire loading for a minimum of 30 minutes."

Before these design recommendations for the detailing of a glass beam can be developed knowledge is needed into glass, its fire performance and current research standing regarding the topic. Experimental research will done to develop new knowledge and understanding. To structure the research a number of sub-questions have been formulated.

- *What are the performance criteria set by Dutch & European building regulations on fire resistant load bearing elements?*
- *What are the properties of structural glass under fire loading?*
- *What research has been done and what are the conclusions?*
- *Which effect do the interlayers have on the resistance of structural glass?*
- *What is the possible explanation for the difference in behaviour between thermally treated and non-treated glass beams?*
- *What application opportunities present itself when structural glass can be implemented as fire resistant building component?*

Production of structural glass

In the production process of glass, a number of methods are used, the method depending on the end product. In this chapter the production process will be discussed for structural glass only. The production of structural glass has two main production processes, namely cast glass and float glass. The choice for either of the types of glass has a strong influence on the appearance, building method and overall design of the structure.

Float glass is the most commonly used production method for building glass. This method is used for all modern window glass as well as laminated glass elements and has been around since the 1950's. Cast glass is an older process in which molten glass is poured into moulds of the desired shape.

Cast structural glass

In the last few years, cast glass has seen an increasing interest in the development of structural cast glass products, ranging from columns to various forms of bricks. Due to structural glass developed as loadbearing element the demand for high quality finishes has become more relevant.

Figure 5 - Molten glass poured in to glass brick mould - source: Faidra Oikonomopoulou - Re3 Glass, Delft University of Technology

Cast glass starts off with a large bath of molten glass from which a certain amount is taken and poured into a mould. When cooled down the glass will have solidified in the desired shape.

The process of cooling down is of great importance in the quality of structural cast glass. For high quality elements it is important that the cooling process is smeared out ensuring that the centre of the poured glass can dissipate its heat in the same rate as the outside of the part. The reason for this is the thermal expansion coefficient of the material, from which surface deformations may form if the rate of cooling is not controlled.

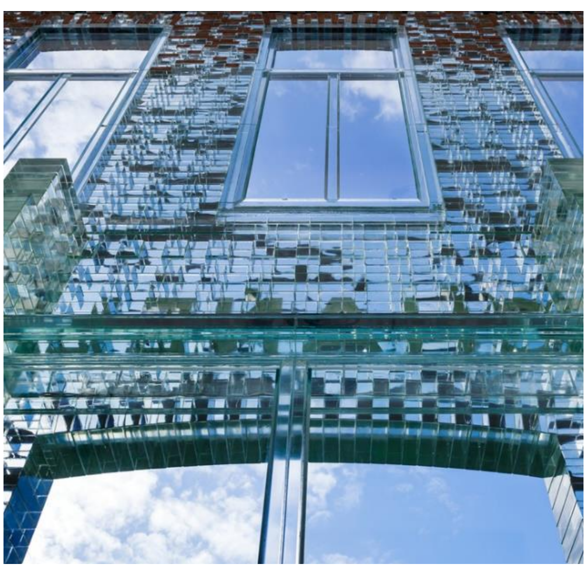


Figure 6 - Cast glass storefront of Chanel, Amsterdam Source: Faidra Oikonomopoulou - Re3 Glass

Cast glass has been applied in a number of architectural projects. One of these projects has been the refurbishment of a monumental façade in the city centre of Amsterdam. The Chanel façade as it is known is built almost entirely from cast glass elements.

During the master course, Dr. Fred Veer gave a course on the development of the production process for the Chanel facade. The bricks had to be developed with a high precision to ensure a perfect vertical façade and eliminate the necessity for large tolerances.

The building process had to be designed and monitored closely. The builders had to be taught how to use UV resin to create the façade. An image of the finished façade can be seen in the image on the left.

Laminated structural glass

Float Glass is the most common of methods, accounting up to 90% of all glass production. The focus in this graduation research will be on float glass since this is the method that is used to produce the laminated glass beams used during testing.
The production method for float glass was developed by Alistair Pilkington around 1950. It starts with a reservoir of molten glass of approximately 1100°C which is poured onto a bath of molten tin and slowly cooled until it solidifies at 600°C. The large sheets of glass, called Jumbo Sheets (3.21 x 6.0 meters) are then treated to several forms of post-processing, depending on the requirements of the final product.

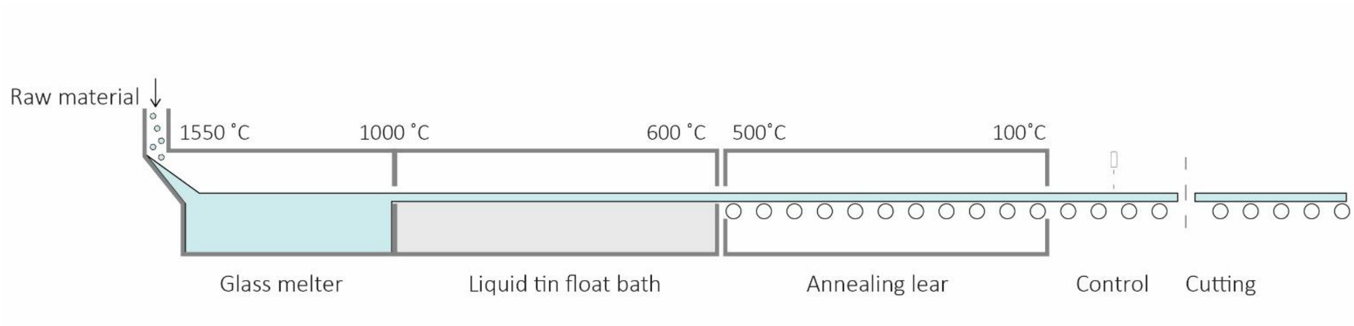


Figure 7 – Schematisation of the float glass production process

After the production of the large sheets of glass, post-processing creates the end product. The plates are cut to the desired size using water jet cutting and the edges are ground and polished off. This is of strong importance to the behaviour of glass due to its brittle behaviour. Small irregularities in the surface of glass may cause early fracture. Grinding and polishing the edges of glass tries to remove these small damages in the materials surface increasing the strength of the glass products.(Schittich et al., 2007; Wurm, 2007)

Thermal treatment of glass

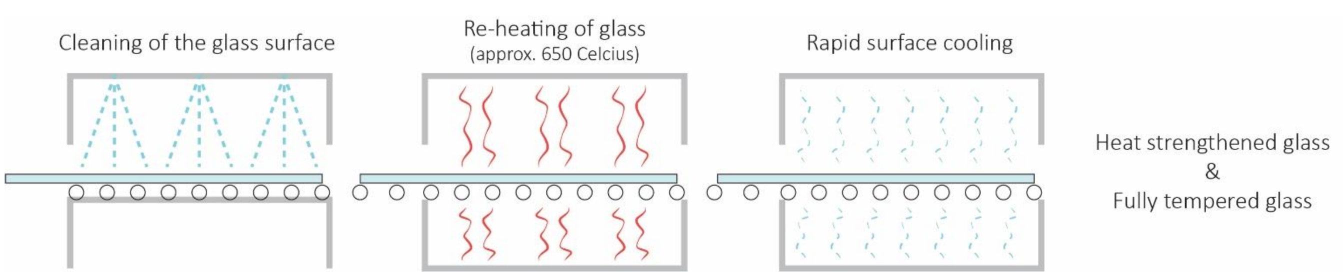


Figure 8 – Schematisation of the thermal treatment of glass panes

After the surface treatment of the glass elements the overall performance and strength can be improved even further. In the surface of cut glass microscopic cracks are present, which have a strong influence in the strength of glass. Under loading of the glass localised stresses occur around these surface microcracks, which in turn can become larger. One method to reduce the effect of microfractures on the structural performance of glass is the process of thermal treatment.

The glass panes are cleaned and re-heated to approximately 650 degrees Celsius. This temperature is just above the glass transition temperature, releasing all internal stresses. When the glass has reached a uniform temperature the glass panes enter the cooling process. Using cool air, the surface of the panel undergoes rapid cooling. Due to thermal expansion properties the outer portion of the glass thickness shrinks. The centre of the glass thickness cools slower than the surface.

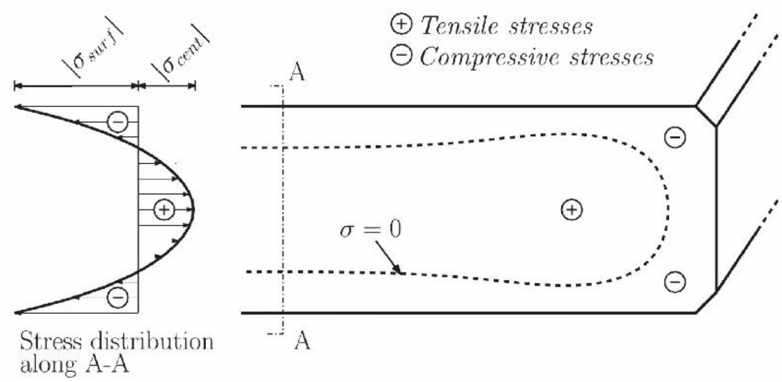


Figure 9 – Schematisation of typical stress distribution in tempered glass
Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

After full cooling of the glass, a compressive pre-stress forms in the outer surface and a tensile pre-stress in the centre of the glass thickness. A schematic representation can be seen in figure 9which shows the corresponding stress distribution through glass thickness and at the edge of the glass. Figure 10 on the right shows the development of the pre-stress in the centre as well as the surface set out in time. What can be seen is the initial tensile stress in the outer surface due to the rapid cooling, the stress formed by the shrinking. Eventually this tensile stress becomes compression as the glass centre shrinks pulling on the outer surface. (Nielsen, Olesen, Poulsen, & Stang, 2010; Schittich et al., 2007; Wurm, 2007)

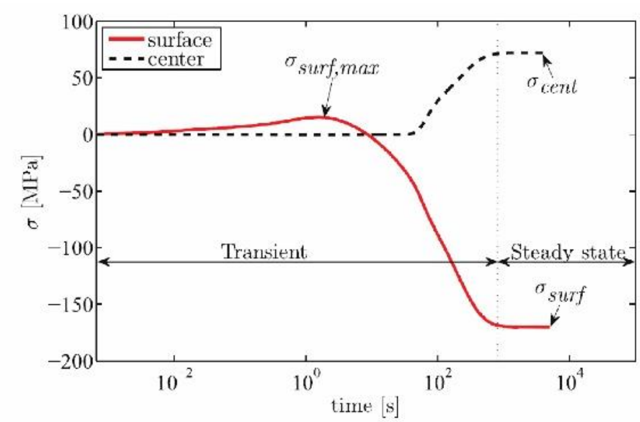


Figure 10 – Typical development of the surface and center stresses during the cooling process
Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

This process can also be induced through chemical strengthening glass by immersing the glass pane in a bath of hot potassium chloride. The compressive stress is induced by a densification of the molecules in the outer surface of the glass. This process only affects a limited depth in the material, leaving the glass vulnerable to surface defects.

Properties of tempered glass

Depending on the cooling rate of the glass a range of tempered glass can be created. The most common are heat strengthened and fully tempered glass. Glass without thermal treatment is referred to as annealed glass. The process of thermal treatment or tempering of glass results in a number of different mechanical properties. According to literature the young modulus is not affected, while the strength of the glass increases. One of the most characteristic properties of tempered glass is the effect on the fracture pattern.

Annealed, non tempered glass fracture with a clean long break from the point of failure to the edge of the pane with large sharp shards. After thermal treatement the induced stresses in the material result in

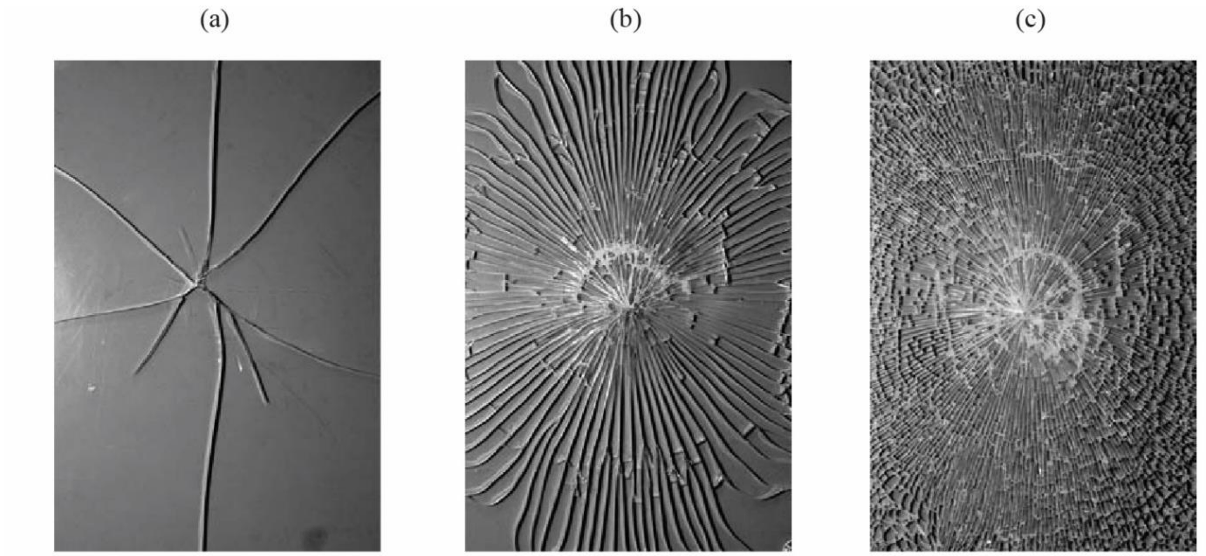


Figure 11 – Fracture behaviour of (a) annealed glass (b) heat strengthened glass (c) fully tempered glass
Source: Fragile yet ductile - Louter

much smaller shards. Heat strengthened glass fractures in narrow shards and the impact dispersses in all directions. Fully tempered glass, which has a higher compressive pre-stress fractures into very small glas dice. Often fully tempered glass is referred to as safety glass due to the very small pieces that are not as sharp. Above, in figure 11 a set of photo's illustrates the difference.

Table 1 – General material properties of annealed, heat strengthened and fully tempered glass

	Annealed glass	Heat strengthened glass	Fully tempered glass
Type of fracture	Large & sharp	Small & softer	Very small dice
Thermal shock resistance	40	100	150
Compressive strength [**MPa**]	200	200	200
Tensile strength [**MPa**]	45	70	120
Youngs Modulus [**MPa**]	72.000	72.000	72.000

The difference in thermal shock resistance may be of importance during the experimental testing. The increased surface compression after thermal treatment increases the resistance significantly.(C. L. P. C. Louter, 2011; Schittich et al., 2007; Wurm, 2007)

Laminating of glass
The last step in the production of laminated structural glass is the actual lamination of the separate members. A laminated element is comprised of at least two glass panes that are laminated together using an interlayer. The full bonding of the surfaces ensures that when one of the panes fractures the element has residual strength, to be able to function until the broken element can be replaced.

A number of methods have been developed to laminate the glass. Depending on the application and requirements of the building element a method is chosen. This is can be a polymer film which can be used to enhance the mechanical strength of the element such as PVB (Polyvinylbutyral) or Sentryglas(SG). Another method to create laminated glass elements is using cast-in-place resin (CIP). The two or more glass panes are fixed at the desired location as a bonding resin is cast in the 1 to 2-

millimetre gap between the panes. The panes are sealed along the edges with a double sided tape to hold the resin.

In the lamination method of PVB or SG, a sheet of the interlayer material is placed in between the glass panes. The parts are heated an rolled to connect the glass and interlayer together. The laminated element is produced in an autoclave, and oven that heats the element under pressure which creates the full surface bond between the glass and the interlayer. This lamination process can result in misalignments between the glass and interlayers, which asks for tolerances in the eventual application.

During the lamination process it is possible to connect or embed other elements in the component. Dr. Louter has created composite glass beams with a steel reinforcement strip in the underside to enhance the strength of the component. A section of this beam set-up can be seen in the figure 12. Other possibilities could be embedding PV-cells in a laminated element to produce energy with a transparent façade of roof.

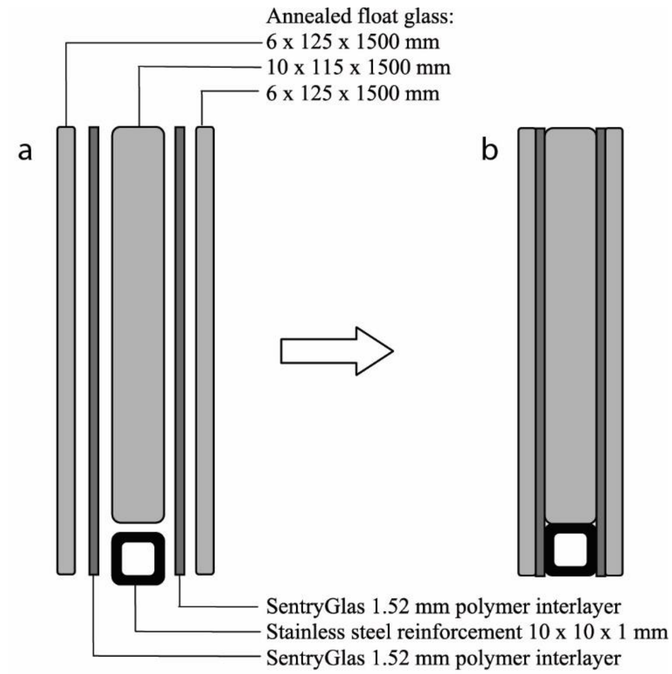


Figure 12 – Section of a steel reinforced laminated glass beam
Source: Fragile yet ductile - Louter

Behaviour of structural glass under fire loading and high temperatures.

Since glass and namely structural glass has become a popular material in current day architecture, numerous studies are done intro the strength of structural components, the failure behaviour of these components and the residual strength of the components after failure. However, the requirements stated by building regulations become more demanding when designers want to apply structural glass in situations where fire safety and fire resistance of structures is relevant.

Glass is characterised by its brittle behaviour and linear elasticity until sudden fracture after exceeding maximum stress. This sudden fracture without warning asks for the residual strength in the form of glass laminates in which the additional glass element acts as back-up in case of accidental fracture, ensuring the loadbearing capability. Laminated glass adds an additional material to the component, which has to meet fire safety requirements as stated by EN 13501-2, EN 1363-1 & 1365-3, which will be discussed in a later chapter of this graduation thesis.

Researchers Kozlowski, Sjostrom, Bedon, Louter, Bawa, Veer & Debuyser all agree that there is a knowledge gap regarding the material properties of glass at elevated temperature and mainly the behaviour of glass when applied as structurally loaded components. This knowledge is crucial to ensure a broader application of structural glass in architecture. (Bawa, Ji, & Lenk, 2014; Bedon, 2017; Debuyser et al., 2017; Kozlowski, Lenk, Dorn, Honfi, & Sjostrom, 2018; C. Louter & Nussbaumer, 2016; Sjostrom et al., 2016; Veer, Van Der Voorden, Rijgersberg, & Zuidema, 2001)

Thermal behaviour of interlayers

Common interlayers constitute a polymer like material binding the elements and transferring shear forces between glass members. These relatively soft interlayers are defined in regards to thermal properties by their low glass transition temperature. As temperature increases the load distribution between glass members will decrease due to the softening of the material. Eventually, the polymer interlayer will decompose and evaporate, thereby losing the composite behaviour in the component.

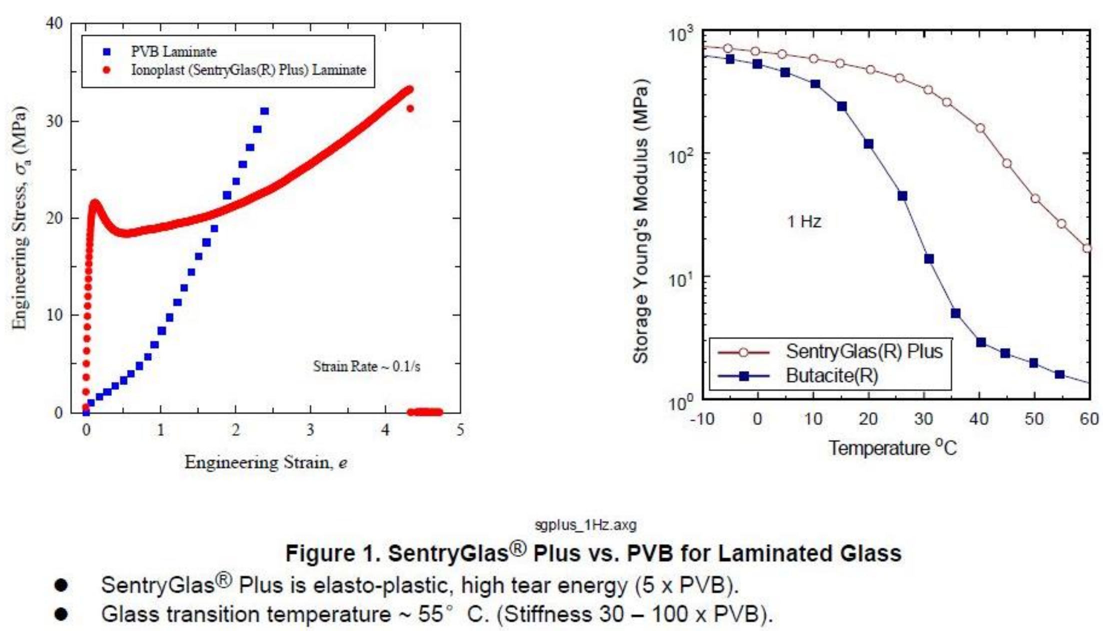


Figure 13 – Stress strain & Young's modulus temperature dependence comparison for SentryGlas and PVB interlayers
Source: DuPont

Kozlowski(Kozlowski et al., 2018) mentions the vulnerability of interlayers, especially when directly exposed to the heating. This leaves the possibility of drop formation and spontaneous burning of the interlayer during excessive heating. The effect of temperature on the young modulus of SentryGlas and PVB interlayers can be seen in figure 13. The properties provided by the manufacturer Dupont show that the stiffer SentryGlas interlayer can withstand slightly higher temperatures than the PVB interlayer before it softens. This difference between the two materials is rather small when we consider that the temperatures registered in the case of fire are well above the decomposition temperature of the polymers.

Thermal behaviour of glass

The transparent material of glass behaves as a perfect linear elastic material. The internal stress increases in a linear manner with added strain. In the figure 14. the comparison can be seen between the elastic behaviour of glass and that of steel. Due to its brittle behaviour the failure of glass is sudden compared to the plastic deformation that steel undergoes. This means that glass does not give a warning before fracture.

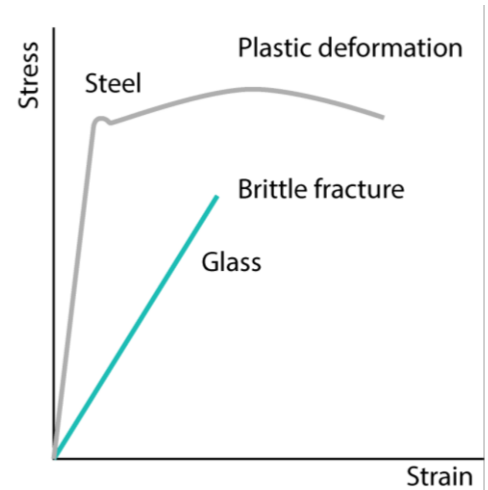


Figure 14 – Elastic behaviour of glass in comparison to steel

Fracture can also be created when glass is exposed to high temperature differences. Glass has a high conductivity which creates large temperature gradients over the thickness of the material. These differences in temperature lead to thermal stress in glass. Kingery(Kingery, 1953) describes the stress formation during the heating and cooling of glass slabs. In the event of cooling the surface of the glass shrinks because of the thermal expansion behaviour creating tensile stresses in the surface of the material, the opposite happening in the centre which is at a different temperature than the surface creating tensile stresses. When heating the material surface wants to expand creating a compressive force and resulting in a tensile force in the centre. A graphic representation can be seen in figure ….

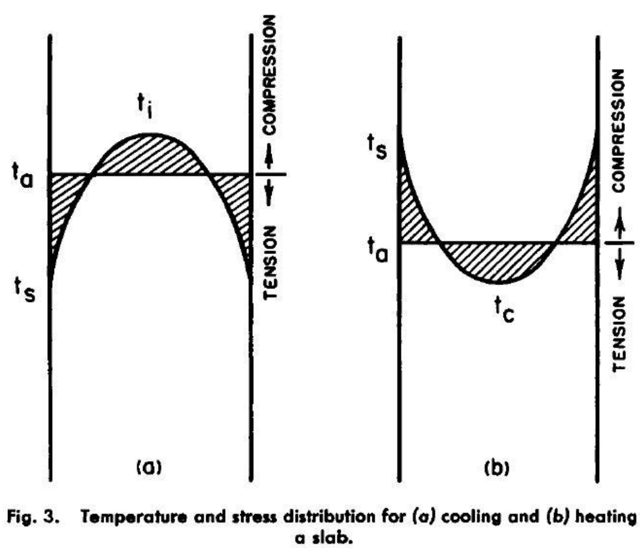


Figure 15 – Temperature and stress distribution for (a) cooling and (b) heating of a slab
Source: Factors affecting thermal stress resistance of ceramic materials - Kingery

During the cooling of heating of the glass element these stresses are increased when the temperature difference is larger. In the event that the stresses exceed the stress or thermal stress resistance the element fracture may occur.

The ability of a glass element to withstand these thermal stresses or thermal shock is classified as the thermal shock resistance of an element. By tempering glass through thermal treatment, the thermal shock resistance can be increased.

The density of glass slightly decreases with the increase in temperature according to Cesar de Sa(Cesar de Sa, 1986). Below the glass transition temperature this decreases according to the thermal expansion coefficient. The density decreases from 2500 kg/m^3 at room temperature to 2474 at 500 Ceslius. Above the glass transition temperature, the density decreases quicker to 2335 at 1400 degrees Celsius.

Sa further describes that the heat transfer in glass is not only influenced by the conductivity of the material per se. He says that “radiation can be considered, for strongly absorbing semi transparent materials, a diffusion process and therefore an effective conductivity that takes into account both processes is usually defined”. Since radiation is an important factor in fire, radiation may have considerable effect on the behaviour of glass beams.

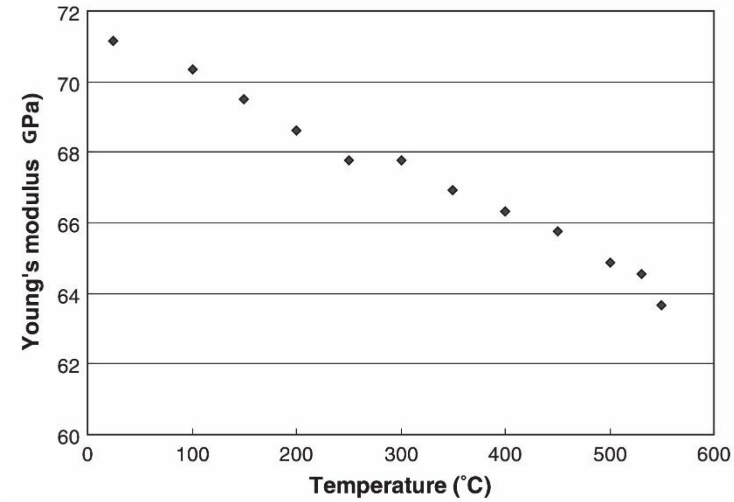


Figure 16 – Temperature dependant young’s modulus of Soda lime silicate Source: Stress relaxation of a soda lime silicate glass below the glass transition temperature - Shen

Research performed by Shen (Shen, Green, Tressler, & Shelleman, 2003)and Rouxel(Rouxel, 2007)describe the effect of temperature on the young’s modulus of glass. Shen measured the temperature dependency of the glass young’s modulus between 0-550 Celsius. He describes an almost linear decrease in the young’s modulus up to 550 Celsius from 71.6 GPa to just under 64 GPa. The data shown in figure … shows his measurements.

Rouxel’s data continues the description of the young’s modulus. With increase in temperature the modulus slightly decreases until the annealing point or glass transition temperature of 527 Celsius. Above this temperature the young’s modulus drops almost steadier until the reaching the softening temperature measured by Rouxel at 727 Celsius. Beyond 727 Celcius the young’s modulus currently has not been measured for standard Soda lime glass.

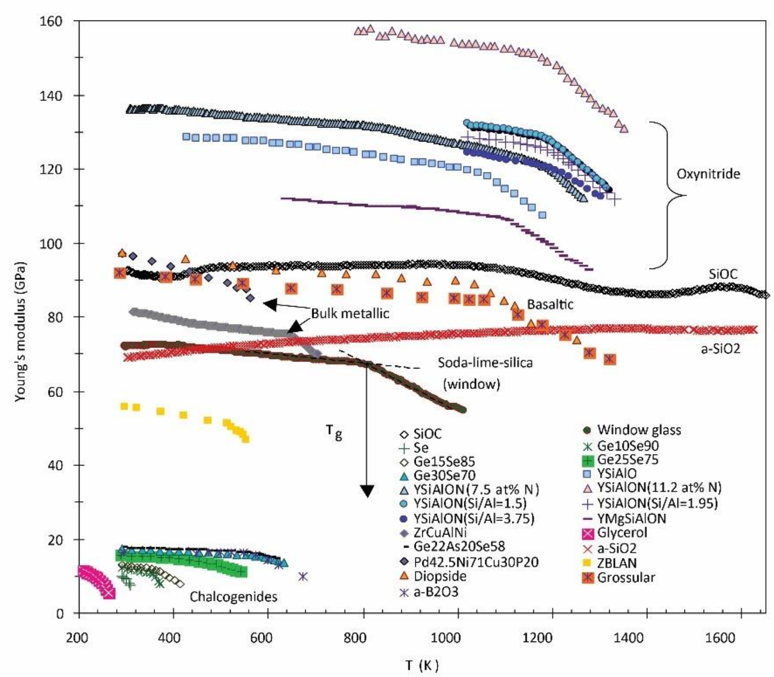


Figure 17 – Temperature dependency of the young’s modulus for a number of ceramics Source: Elastic Properties and Short-to Medium-Range Order in Glasses - Rouxel

Zahra Nodehi(Nodehi, 2016) did her master thesis on the behaviour of structural glass under high temperatures and realised that the material properties of soda lime glass had not been tested above 727 Celsius. During her research she simulated the fire resistance tests at EMPA in Diana. She had to estimate the Young's modulus values above 727 Celsius do replicate the test conditions. In this graduation research the values that she used will be used in the simulations.

These factors describe the thermal properties of glass. The eventual resistance of structural glass elements not only depends on the properties of the materials but perhaps more importantly on the detailing and set-up of the elements in a structural matter. The following research has investigated the performance of glass and structural glass under heating and fire loading. A summary is given for each.

Fire testing of structural glass beams; Initial experimental results - Louter

Research performed by Louter (C. Louter & Nussbaumer, 2016) tests 3 layer glass laminated beams. The test is performed above a fire furnace at the research facility of EMPA in Switzerland. During this test laminated glass beams were tested above the fire-furnace in a 4 point bending set-up. During the test each beam was loaded with a static load of 115 kg. The set-up as pictured in figure 18 shows the glass beams spanned above the fire-furnace, wrapped in insulating panels(yellow) of promatect to protect the mechanical loading mechanism from the high temperatures of the furnace. These panels are placed between the beams, aligned with the top edge of the beams. This results in the top 30 millimetres of each beam covered and protected from direct heating by the oven. Each beam has a height of 100 millimetres, the bottom 70 millimetres are directly heated during testing.

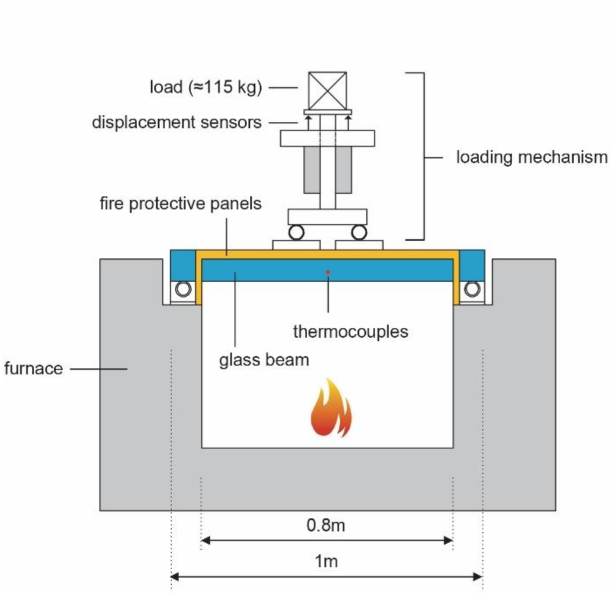


Figure 18 - Test set-up at EMPA
source: Fragile yet ductile – Dr. C. Louter

Furthermore, the outer 100 millimetres of each side of the beam is protected by another panel of promatect, which results in a cool support situation protecting the outer 100 millimetres on each side of the beam to heat up by direct fire loading.

The fire furnace replicates a computer controlled standard fire curve as prescribed by NEN EN13501-2. Temperature reaching 800 C in about 20 minutes.

Louter performed 3 tests in which the 3 beams above the oven differed in thermal treatment of the glass elements, namely annealed, heat-strengthened and fully tempered glass. Set 1 used a PVB Interlayer in the laminate, set 2 SentryGlas and set 3 was a PVB set reinforced with steel in the bottom of the middle pane.

The results from this test showed that glass laminated beams have the potential to withstand fire loading for a significant period of time. The failure time was well over the minimal requirement of 30 minutes, reaching times above 40 minutes. One of the interesting observations in the results is the sequence of failure in order of thermal treatment, annealed failing first followed by heat-strengthened and lastly fully tempered. This behaviour was observed with each set of beams.

The results from the test may however have been favoured by the set-up of the beams. As mentioned the top 30 millimetres of the beam were protected from fire loading which could have had influenced the failure time of the beams. The glass and the according interlayer may have remained relatively cool compared to the area that was fully heated. However, the measurement of temperature was performed 30 millimetres from the bottom of the beam, thereby making it difficult to determine the temperature of the top of the beam.

The same can be said for the supports which are protected from direct fire loading. This creates a strong temperature gradient between the glass loaded by the heat and the cool supports on either side. However, this did not lead to thermal shock due to the temperature difference inside the beam. Rather,

it resulted in the maintained composite action of a 3 layered laminate, while the interlayer had fully evaporated in the middle of the beam.
The last remark on the test as Louter concludes is the rather small load of 115kg, which can have a positive effect on the overall failure time of the beams.

Behaviour of structural glass at high temperatures – Nodehi

As follow up on the experimental research performed by Christian Louter at EMPA, MSc graduate student Zahra Nodehi(Nodehi, 2016) conducted tests to further investigate the behaviour of structural laminated glass at high temperatures. First off, she attempts to replicated the temperature results from the EMPA tests in a FEA (finite element analysis) using the software of Diana FEA. This could become critical in further investigation of structural glass build-ups to simulate the fire resistance and heating-up of the glass, limiting the need to perform expensive large-scale fire tests.

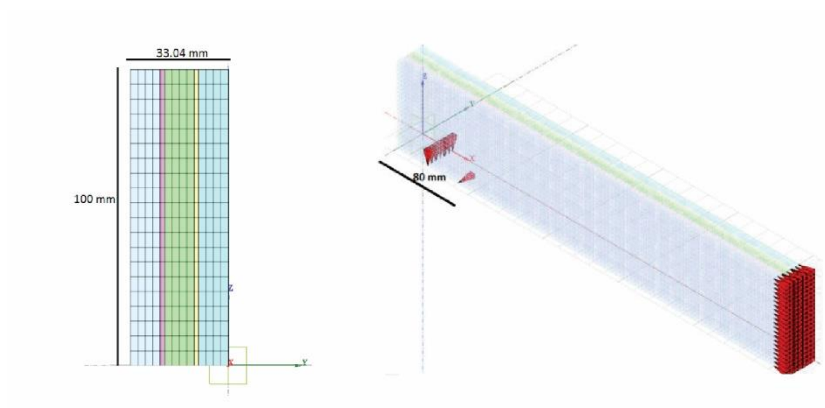


Figure 19 – Diana simulation model of half a beam, based on the EMPA test
Source: Behaviour of structural glass at high temperatures - Nodehi

In her finite element model, she applied the material properties of glass & SentryGlas interlayer including the temperature dependant properties such as thermal conductivity, specific heat and young's modulus. In her modelling she concludes that the temperature dependant material properties of glass have further improve the values retrieved from her simulations.
However, the values of the young's modulus for glass are currently not known for temperatures above 600 C, while temperatures of close to 820 C have been measured in the EMPA test performed by Louter(C. Louter & Nussbaumer, 2016). Therefore, she attempts to make a estimation of the young's modulus values between 600 C and 820 C, which strongly influences the results. She does conclude that the values obtained from Rouxel(Rouxel, 2007) produces results that match the results from the EMPA test. From her FEA she concludes that finite element software has the ability to approach the behaviour of glass in fires. She continues her MSc research by performing fire furnace tests at Efectis in Bleiswijk. She performed a series of six tests in a large-scale fire furnace. She tested panes of 1500 x 300mm x 10mm supported either lying on the long face or standing on the long edge supported by a steel roll on either side spanning 1,5 meters.

The fire furnace in her test is set to heat up according to a standard fire curve, similar to the fire curve applied in the experimental research of Louter. Unfortunately, the first experiments only took a matter of minutes due to early thermal shock occurring near the supports. During the first few minutes the oven quickly climbs to 500 C and heating the glass as well as the steel support. Due to the different material properties of steel and glass the temperature of the glass was higher than the steel. This

Figure 20 – Set-up of two glass panes above the fire furnace at Efectis Source: Behaviour of structural glass at high temperatures - Nodehi

combined with the outer edge of the glass being unaffected by the increase in temperature due to the steel support a strong temperature gradient is built up between glass loaded by the fire furnace and glass slightly protected by the supports.

She attempts another set of experiments in which the entire pane of glass is placed inside the oven, eliminating the temperature difference in the glass pane. She runs this test for annealed glass that unfortunately fails due to thermal shock. In further attempts she adds promatect between the steel support and the glass which seems to eliminate the effect of thermal shock, although not for each test. In the tests using heat strengthened and fully tempered glass the panes fail after serious plastic deformation. The results from this test show that between 550- 600°C the glass transition temperature is reached and the pane deforms plastically.

From her research she concludes that it is of strong importance in the design of fire-resistant structural glass to keep the temperature of the glass below the glass transition temperature of 550-600 C. In her tests heat strengthened and fully tempered glass started deformed plastically at 550-600 C. Above this temperature glass has lost its surface compression and changes from a linear elastic material to a ductile material which deforms plastically, in turn losing its ability to carry any form of loading, including self-weight.

She states that for structural glass, supports must be detailed in a clever way with respect to thermal shock between glass and the support material.

Finally, her recommendation for the development of correct finite element analysis is to fill the data gap in young's modulus to precisely predict the behaviour of structural glass at high temperatures.

Behaviour of monolithic and laminated glass exposed to radiant heating – Debuyser

The experimental research performed for this research paper attempts to develop an understanding of the radiation absorption and internal conduction to eventually develop a model to understand the behaviour of glass at elevated temperatures.(Debuyser et al., 2017)

The test set-up consists of a radiant panel that is place at a specific distance to glass mounted in a support frame. In total 20 glass specimens are tested with laminated and monolithic specimens varying in thicknesses, different interlayers and with or without low-e coating.

The radiant panel is heated up before the glass is loaded by covering the panel until it reaches a stable situation. During testing temperature is measured with thermocouples on the exposed surface, inside the interlayer and at the back of the glass.

The results show that the transmittance, absorptance and reflectance of the glass is constant regarding time and temperature of the glass. The absorptance however increases with increased glass thickness, more material higher absorptance. The results show that absorptance can be reduced significantly by using a low-e coating, this result is also found in research performed by Csoke & Koudijs(Csoke & Koudijs, 2012)

In the process of radiant heating the exposed glass pane in monolithic as well as laminated specimens crack at a temperature difference of 50 C between front and back of the glass pane. This crack, due to thermal shock, occurs before the first decomposition bubbles form in the interlayer of laminated specimens. For PVB interlayers these bubbles develop at a temperature of 90 C while for SentryGlas interlayers they develop at 150 C.

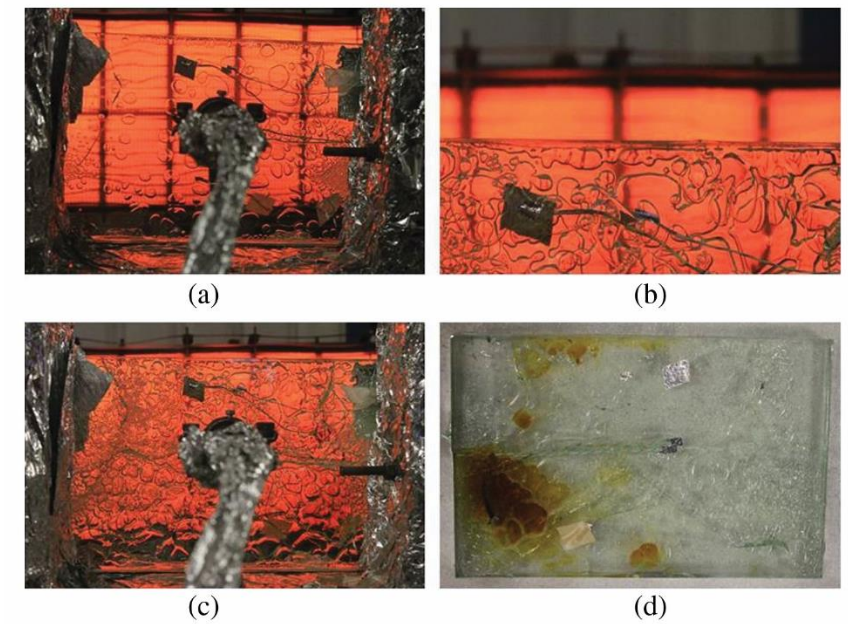


Figure 21 – Stills of the radiant heat testing, showing decomposition bubbles of the interlayer. Source: Behaviour of monolithic and laminated glass exposed to radiant heating - Debuyser

Even though this research focusses mainly on radiant heating, compared to standard compartment fires the conclusions are interesting in respect to fire safety design of structural glass. From these results a difference is found between a PVB and an SG interlayer, mainly on the occurrence of bubbles during the decomposition of the interlayer creating the impression that SG interlayer might be more interesting when designing for structural glass with the intention of fire resistant structural glass since an interlayer that can withstand higher temperatures would be beneficial.
The analysis that transmittance absorptance and reflectance is constant regarding time & temperature is and interesting conclusion that could point to the fact that the thermal coefficient of glass does not change with elevated temperatures.

An experimental study on glass cracking and fallout by radiant heat exposure –Harada

In earlier research on the effect of radiant heat exposure in regards to the cracking of glass, Kazunori Harada(Harada, Enomoto, Uede, & Wakamatsu, 2000) tested a total of 50 specimens of float and wired glass loaded by radiant heating. During the test a radiant heat panel was placed at varying distance to the glass pane, thereby altering the radiant heat flux with which the panel was loaded ranging between 3 – 10 kW/m^2. As in the research performed by Debuyser(Debuyser et al., 2017) the glass specimen was loaded with the full force of de radiant panel by first shielding the radiant panel and removing this shield when heated up. The glass specimen is thereby not gradually heated with a time dependant increase but hit with a sudden heat load. The eventual goal of the experimental research was to determine a critical heat flux at which breakage would start to occur.

From the experiments a strong difference is witnessed between the float and wired glass, float glass withstanding the heating for a longer period of time than the wired glass. From the data collected during the experimental research the critical heat flux at which wired glass cracked was 2.0 kW/m^2 compared to 5.0 kW/m^2 found for float glass specimens. As the heat flux increases the time it takes before cracks develop in the panes decreases.

A result that was not concluded by Kazunori but can be observed from the table of results is the temperature difference between the centre of the glass and the outer edge at initial crack. Wired glass cracked at an average temperature difference of 22 Celsius and the float glass specimens cracked at an average temperature of 50 Celsius. This same temperature for float glass was also found in later research performed by Debuyser.

Using transparent intumescent coatings to increase the fire resistance of glass and glass laminates – Veer

Research into the fire performance of overhead structural glass beams uses a 4 point bending set-up to investigate the behaviour of a number of glass beam combinations. According to Veer(Veer et al., 2001) there is some data available for a glass façades with metal structural elements, however nothing is know about structural glass in overhead constructions such as glass beams.

The 4-point bending test uses weights that enforce a stress with a maximum of 24 MPa. The beams are loaded by a propane burner on one side of the beam with a flame at a constant temperature of 650 Celsius. On the other side of the beam a surface thermocouple measures the temperature.

The beams compositions test beams with annealed glass, chemically toughened glass, chemically toughened in combination with polycarbonate foils and a special laminate with an insulating cavity. Each beam is tested without addition and a version which has a layer of intumescent coating applied. The intumescent coating is Flameguard HCA-TR.

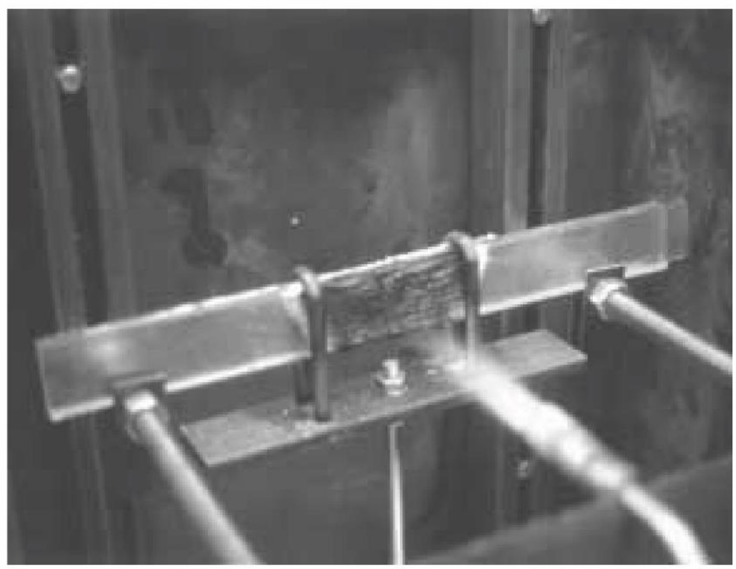


Figure 22 – Burner 4 point bending set-up
Source: Using transparent intumescent coating to increase the fire resistance of glass and glass laminates - Veer

Table 2 -Results of the testing performed by Veer

Configuration	Time to failure	Conditions of specimens at end of test
A without load	>30 minutes	Intact
A	2.4 minutes	- Broken
A + intumescent paint	19 minutes	- Broken
B	>40 minutes	Intact
B + intumescent paint	>40 minutes	Intact
C	>30 minutes	PolyCarb evaporated
C + intumescent paint	>30 minutes	PolyCarb evaporated

D D + intumescent paint	1.45 minutes 4.1 minutes	Cohesive failure between segments Cohesive failure between segments
E E + intumescent paint	>30 minutes >30 minutes	PolyCarb core shows melting PolyCarb core shows melting

From the tests, Veer discusses that annealed glass in unsafe to apply as structural glass element while the toughened glass shows potential since the elements are resistant against the fire loading. Furthermore, he draws the conclusion that the performance of glass beams can be improved using an intumescent coating. The Flameguard HCA-TR improves the failure time of a few of the beams. The main effect of the intumescent coating is the slowed down heating of the glass and interlayer and slowed down development of thermal strain in the two materials.
Based on these results, the HCA-TR intumescent coating is considered to use in a later test of this graduation research. During test 4, with modified HS PVB beams, the HCA-TR is used.

Fire resistance of glass – Bokel, Veer

This small conference paper(Bokel, Veer, & Tuisinga, 2003) discusses the effect that well-known commercial fire protective products have on the actual performance of building products. In the paper the failure of glass is described to occur either from failure to the surface of to the glass edges. Two methods are proposed to test these failure behaviours of glass elements.

These glass elements are protected using Pyroguard epoxy resin and a cheap laboratory prepared expoy to check the difference in performance of the commercial product. The paper only tests small beams of 400mm long and 40 mm in height with varying thicknesses. The beams are placed in a 4 point bending test that loads the beams using weights, similar to the research of Veer(Veer et al., 2001).

The conclusion that can be drawn from the test is that the commercially available Pyroguard, which is supposed to protect elements in fire situations performs a lot less than the laboratory epoxy. The lab epoxy performs a factor 3-6 times better than the commercial product.

In the conclusions, it is mentioned that the test set-up needs further development and that additional testing should be done to validate the results against a wider range of products. To the authors knowledge this has not yet been done or not been published.

Figure 23 – 4 point bending set-up used by Bokel
Source: Fire resistance of glass - Bokel

Fire safety engineering and Fire resistance of the built environment

When we speak about fire engineering in the built environment there are two main subjects, namely fire safety design in building and the fire resistance of materials applied in the built environment. Fire safety focusses on facilitating safe evacuation of people inside buildings in case of fire, whereas the fire resistance of building materials only focusses on the technical performance of a single or combined building element.

In the Netherlands (NEN-norms) and the European Union (EN-norms), building regulations state the requirements in regard to fire safety engineering as well as the fire resistance that building materials should be able to achieve. Currently there are no specific regulations in respect to structural glass yet, rather loadbearing structural glass components and the building in which these components are applied are subject to the relevant building regulations.

To be able to determine precisely which regulations apply on structural glass the general building requirements and specific requirements on loadbearing elements will be described.

Fire safety design of buildings

An important part of the design of buildings has to do with the incorporation of fire safety design in buildings. In the case of fire breaking out in a building the occupants using the building should have access to evacuation routes and sufficient time to exit the building. The requirements for fire safety differ according to the type and size of the building. Large public buildings have more strict fire safety requirements than a small household has.

Buildings are divided into so called compartments, these compartments are regarded as separate rooms in case of fire. A fire compartment should be able to offer occupants of this compartment access to a neighbouring compartment, a smoke & fire free passage or a designated fire escape. The compartment should in turn be able to provide an evacuation time for occupants of at least 30 minutes in which time the compartment is able to withstand penetration of smoke, heat and flames. This minimal containment time stated for compartments can increase depending on the function, the size, the occupancy and more. These requirements for the fire safety times of residential and non-residential buildings are stated in the Bouwbesluit 2018 Afd 2.2 & 2.12. In table 1 and table 2 a summary is given.

Table 3 -The performance criteria of building components for Residential buildings

Residential	Minimal time of resistance
In the case no floor of a compartment is situated above 7 meters above ground level	60 min
In the case a floor of a compartment is situated above 7 meters above ground level and no floor is situated 13 meters above ground level	90 min
In the case a floor is situated above 13 meters above ground level	120 min

Table 4 -The performance criteria of building components for Non-residential buildings

Non-residential	Minimal time of resistance
In the case no floor of a compartment is situated above 5 meters above ground level	60 min
In the case a floor of a compartment is situated above 5 meters above ground level and no floor is situated 13 meters above ground level	90 min
In the case a floor is situated above 13 meters above ground level	120 min

However, for each required time of resistance 30 minutes can be subtracted if the floor is not above either 7 meters in residential or 5 meters in non-residential and the internal fire load is a maximum of 500 MJ/m^2.

Since structural glass is yet to be classified as fire resistant in this thesis the focus will be on achieving a minimal fire rating of 30 minutes, thereby fulfilling the minimal requirement for compartmental containment.

General fire classification of building materials – NEN EN 13501-2

The European committee for standardization provides the generally accepted and enforced European Standard in building products. Beside general building standards and regulations, the committee has addressed the spread of fire and smoke and the effect of these two on the loadbearing capacity of a construction.
In order to apply a new building product in a building or construction, manufacturers have to prove the fire resistance of loadbearing or separating elements. This is done through experimental testing after which products that live up to the stated standards are certified for use.

Loadbearing and separating elements are tested according to levels of 'Thermal Attack'. In total there are 5 defined levels of thermal attack that are covered by NEN EN 13501-2(European Commitee for Standardization, 2016).

Standard temperature / time curve (post flash over-fire)
This model describes a fully developed fire in a compartment of a building. As the title states the temperature is described as a function of time.
The development of the temperature can be seen in figure 24. The temperature is defined by the following function:

$$T = 345log_{10}(8t + 1) + 20$$

t = time from start of test (min)
T = mean furnace temperature (˚C)

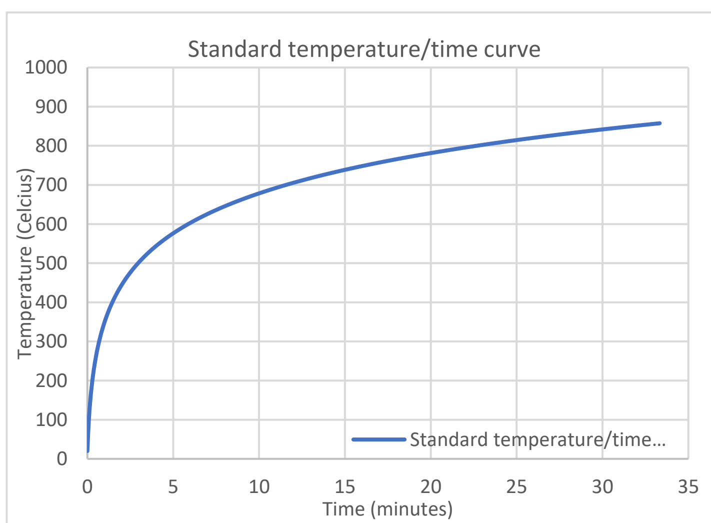


Figure 24 – Temperature plot of the standard fire curve

NEN EN 1363-1 described further details of the standard temperature / time curve.

1. **Slow heating curve** (smouldering fire)
   This thermal attack model is only to be used if it is expected that the fire resistance of an element will be affected by the temperatures in the growth stage of a fire. This is relevant for elements that are strongly affected by temperatures below 500 ˚C. Examples of elements could be intumescent coating or other reactive elements.
2. **Semi-natural fire**
   During this test the temperature of gases will quickly reach 1000 ˚C within 10 to 20 minutes from the start. This test is performed since the high convective heating is hard to achieve during standard fire furnace tests. This attack is achieved by a fire from softwood cribs.
3. **External fire exposure curve**
   And external wall can be tested in regard to fire resistance from external fires or fires that emerge through a window.
4. **Constant temperature attack**
   Certain elements can be tested by loading the element with a specific constant temperature. These temperatures depend on the application of the element. The values are 20 ˚C, 200 ˚C, 500 ˚C and 1000 ˚C.

NEN EN 13501-2 further states the performance characteristics of building elements. The loadbearing capacity and/or integrity and/or insulation have to be assessed according to national regulations. The thermal performance characteristics are explained below.

R – Loadbearing Capacity
Defines the ability of a construction element to withstand fire exposure during a certain period of time while maintaining its structural stability. For floors, roofs and beams and other flexural loaded elements the criteria considered are the rate of deformation (rate of deflection) and a limit state for the actual deformation(deflection). More on this in NEN-EN 1363-1

E – Integrity
Elements with a separating function a tested for their ability to withstand fire exposure on one side only, without transmission of fire to the unexposed side occurring. The passage of flames or hot gases may cause the ignition of the unexposed surface or other materials adjacent to the surface. The integrity is determined on the basis of three aspects namely, cracks or openings in excess of given dimensions, ignition of a cotton pad, sustained flaming on the unexposed side.

I – Thermal Insulation
The classification of thermal insulation is based on the ability of a building element while exposed to fire from one side, while limiting the specific heat transfer from the heated to the non-heated side. This classification limits the event in which either the unexposed surface or materials in close proximity. Furthermore, the element will provide a heat barrier to protect people nearby.

Additional optional characteristics are described by NEN EN 13501-2; however, these are not relevant for structural glass beams and therefore not discussed.

General requirements of fire resistance testing – NEN EN 1363-1

The experimental testing performed during for this graduation thesis focuses on the standard fire exposure conditions as stated by NEN EN 13501-2. The procedures and requirements for the eventual certification of a building element are given in NEN EN 1363-1(European Commitee for Standardization, 2002). The document focusses on the requirements set on equipment, the specific test conditions, the procedure during testing and the failure criteria. A few of the relevant aspects will be discussed here.

The fire furnace that is to be used is not specified by an exact model or product type but rather explains what the properties of a fire furnace should meet. Important but self-explanatory is the capability of providing standard fire exposure conditions with respect to thermal exposure.
The lining of a furnace should have a density lower than 1000 kg/m^3 with a minimum thickness of 50 mm and has to cover at least 70% of the exposed surface. Depending on the element that is tested furnaces have specific requirements. For beams it is stated that beams should be heated on 3 or 4 sides, appropriate to the application of the beam.

The heating curve as already stated in NEN EN 13501-1 is explained to be the average temperature in the oven. This document states the tolerances allowed as percentage deviation during specific time steps.

- 15% between 5-10 min after start of the test
- (15 – 0,5(t-10)) % between 10-30 min after start
- (5 – 0,083(t-30) % between 30-60 min after start
- 2,5 % from 60 min after start

d_e percentage deviation

$$d_e = \frac{A - A_s}{A_s} x\ 100$$

A Area under the actual furnace temperature/time curve

A_s Area under the standard temperature/time curve

t Time in minutes

The document also describes the criteria that determine if the element has failed and when this failure occurs. A distinction is made between vertically loaded and flexural loaded elements. This research focusses on beams, flexural loaded structural glass beams, the criteria stated will be explained.

The loadbearing capacity of a structural beam is determined by the number of minutes for which the element maintains the ability to support a representative load during testing. The standard for failure is based on two criteria in regard to displacement. First is the maximum deflection and second describes the rate of deflection. Failure to support the load occurs as soon as one of the two criteria is exceeded.

- Limiting deflection $D = \frac{L^2}{400\ d}\ mm$
- Limiting rate of deflection $\frac{dD}{dt} = \frac{L^2}{9000\ d}\ mm/min$

Fire resistance testing for loadbearing elements; Part 3 Beams - NEN EN 1365-3

Building elements or classes of elements have a specific norm that states what the requirements are to determine the fire resistance of an element. For loadbearing elements, the norm NEN EN 1365 is applicable. This norm consists of 6 separate parts that describe the method of testing that should be performed for varying loadbearing elements.

Part 3 focusses on loadbearing beams, which is relevant for this research. Tests into the fire resistance of structural loadbearing beams have to be performed according to the general requirements stated in NEN EN 1363-1 combined with the specific requirements for beams in NEN-EN 1365-3(European Commitee for Standardization, 2001). This norm or standard describes the requirements regarding the test specimen, in this case a beam, the method of installation, the test procedure, the measuring instrumentation and describes the building elements covered by the report and results. The relevant content for the testing performed in this research are regarding the installation and procedure of testing.

Exposure

- A beam is exposed to fire loading across a certain exposed length, the remaining and unexposed length of the beam may not be more than 200 mm on each end of the beam.
- A beam only heated on three sides in any application, when supporting a floor for example, should be tested with a representative material on top.
- During testing all the non-exposed parts of the beam, must be sealed of with mineral wool to close off all possible leakages to stop hot gasses.

Loading

- The load on the beam during testing must replicate the maximum bending moments and shear forces representative to or higher than with a beam in practice,
- The displacement measured during the test will be measured as the starting value after applying the load.
- The test set-up may not affect the performance of the beam in regard to structural capacity apart from heating and the applied load case. The additional materials may not increase the structural performance, limit the possible deformation or any similar situation.

A large portion of the requirements stated by NEN EN 1365-3 refer back to NEN EN 1363-1 and specify that the method shall live up to this standard while testing loadbearing beams.

Methodology

Experimental testing is used to increase the knowledge into the behaviour of structural glass under fire loading. Laminated structural glass beams will be placed in a test set-up designed to load the glass beams while they are heated by a fire furnace. The test set-up is based on previous test done at EMPA.

During the physical test one variable will be adjusted to be able to compare the data from the previous experiment. In the test performed by Dr. Louter(C. Louter & Nussbaumer, 2016), the top 3 centimetres of the total of 10 centimetres was protected from fire loading. The one variable that will be adjusted is the surface heating of 3 full sides of the laminated beam. The first tests will focus on standard factory ordered laminated glass beams, to determine their behaviour.

Based on the results that follow from the experimental testing a set of 3 identical beams is modified to increase the fire resistance. These beams will be tested in the same manner as the first test to see what the effect of the modification is.

The final goal of the project will be to develop design recommendations for glass beams that are able to withstand fire loading for at least 30 minutes as stated by building regulations. Thereafter, a case will be handled to show the opportunity of implementing fire resistant glazing in architectural constructions.

Fire furnace testing of glass at Efectis

In the early start of this MSc graduation project the company of Efectis offered to use their certified fire furnace to test structural glass specimens. Efectis is a company that provides testing, modelling and certification of a broad range of building and industry products. The experimental set-up used during the tests will be described in this chapter to ensure that the testing can be replicated. The chapter will describe the following topics:

- The glass specimens
- The fire furnace
- Monitoring equipment
- Testing rig

Figure 25 – The test set-up is hoisted on top of the fire furnace at Efectis

The Glass Specimens

The beams used in the fire furnace test come from a batch of beams ordered for former research performed by Louter. The glass panes in a beam are standard Soda lime silica glass laminated with either PVB or SentryGlas interlayers.

The composed beam has a length of 1 meter with a section of 33.04 mm x 100 mm. As can be seen in figure 27 the section is built up from three glass element of 10mm x 100 mm laminated with and interlayer of 1.52mm. Inside each interlayer, approximately 30 mm from bottom of the beam, thermocouples are laminated in place.

Figure 27 – Three glass beams placed in the test set-up, seen from beneath

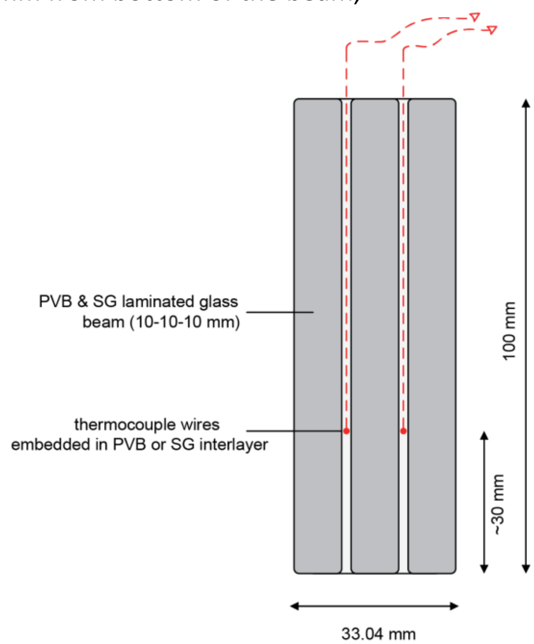


Figure 26 – Section of one of the laminated glass beams, based on an image of Louter

The beams with product name Swisslamex ordered by Louter were produced by GlasTrösch AG, Bützberg Switserland. From the available 16 beams that remained after the tests performed at EMPA in Switserland, 12 beams were used in this study. In total there were 6 types of beams, these are listed below.

Table 5 -

	Annealed (Float)	Heat Strengthened (TVG)	Fully Tempered (ESG)
PVB Interlayer (used)	2 (1)	5 (4)	2 (1)
SentryGlas Interlayer (used)	2 (2)	3 (2)	2 (2)

Fire Furnace - Efectis

Tests are performed above a certified fire oven provided by Efectis. The oven has been designed to replicate situations relevant to a broad range of fire resistance and safety testing. Clients build up an element that is to be certified. This element is placed in front or on top of the oven, the other side is closed off. In the figure below the testing rig for this research is situated on top of the furnace with all attached monitoring devices connected to the adjacent computer.

To mount the testing rig a so-called OR-frame is used in which the rig is built. This OR-frame, provided by Efectis has the exact dimensions that fits on top of the oven. This allows to lift the rig in its entirety on and off the oven, in turn ensuring easy access to the rig for build-up.

The oven uses has 3 propane burners that produce the temperature increase as stated by a standard fire curve in NEN EN 1363-1. During the test the intensity of the burners can be regulated by employees of Efectis to match the standard fire curve and to make sure the temperature does not exceed the maximum tolerance described in the European norm.

To make sure that each test starts from relatively cool oven, the oven has to cool down between tests. This is to make sure that the heat capacity of the inner lining of the oven has enough time to dissipate all the stored heat, not to affect the test. This took about 2-3 hours to cool down to room temperature, leaving time to fit a new set of beams before placing the test rig back on the oven.

To place the test rig nicely on top of the oven a so-called OR-Frame is used. The OR-frame, provided by Efectis, is a rectangular steel frame with fastening points to attach an overhead crane. The testing rig is built inside the OR-frame to easily lift the rig on and off the oven.

Figure 28 – Small fire furnace at Efectis with the test set-up on top and all measuring equipment hooked up to the computer, Bleiswijk – The Netherlands

Monitoring Equipment

The tests performed at Efectis have been monitored thoroughly. Continuous measurements are taken during the testing and documented for later analysis. For the purpose of possible reproduction of the performed tests each monitoring device will be described.

Temperature monitoring

The temperatures are recorded in the test specimen as well as the temperature inside the oven. Thermocouples are sensors that measure the temperature with the use of two different metal alloys. The thermocouples are connected to the main computer which collects al the retrieved data.

The thermocouples used in the set-up are Type K couples, which use the alloys Nickel-Chromium as positive conductor and Nickel-Aluminium as the negative wires.The thermocouples work due to the dissimilar properties of the two used alloys. When temperature changes, a slight voltage is measured due to thermoelectric effect, which can be measured.

Plate thermocouples are used to measure the oven temperature, this is the required method in accordance with NEN EN 1363-1. The oven temperature is measured at 4 locations inside the oven near the glass beams. The thermocouples are placed in pairs of two between two glass beams and one on the side of each support. Furthermore, the ambient temperature outside the oven is also measured. These couples are provided by Efectis during each test.

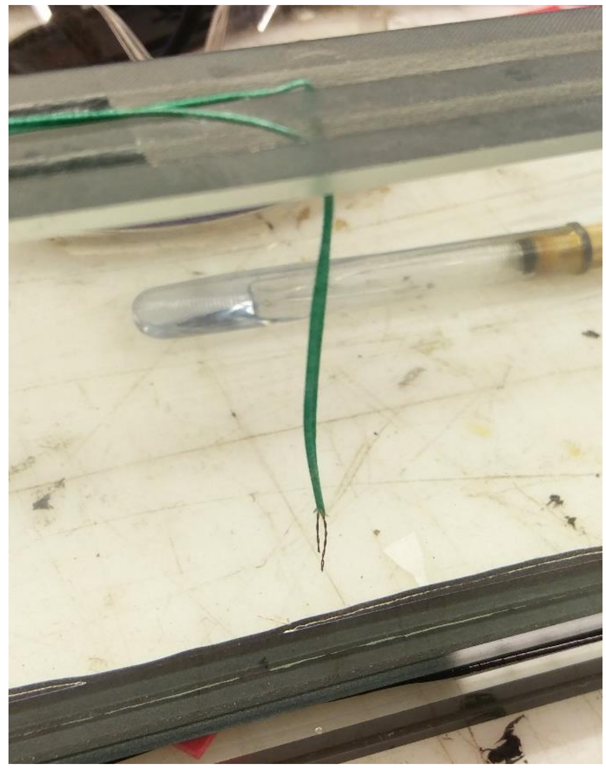


Figure 29 – Laminated thermocouples inside glass beam

The glass beam temperature is recorded with the use of thermocouples laminated into the interlayer between the three glass panes. An image of this can be seen in figure 29 The head of the thermocouple is placed approximately 30 mm from the bottom of the beam and the wire comes out on top of the beam. These couples were pre-laminated and ordered from Swisslamex.
The thermocouple wire from the beam is attached to Type K In-line miniature plugs, which are extended using a more durable cable from Efectis, this cable is has a glass fibre mantle. Attaching the plug to the wire is a delicate process due to the fragile wires of the thermocouple and need to be handled with care.

Displacement monitoring

The glass beams are tested until they eventually fail. This failure is determined by either the rate of displacement or the overall displacement of the beam. To measure the displacement of the beams, analogue displacement sensors are used. The sensors are manufactured by AE sensors, an image can be seen on the right in figure 30

Each beam has two sensors to measure the displacement, on connected to the top middle of the beam which is where the maximum displacement of a beam takes place. This location is however subjected to the heating of the oven, with the risk of letting go. As a back-up another sensor is fastened to the load, which will displace similarly as the other location. The sensors are attached to the beam and the load using a thin stainless-steel cable with a diameter of 0,45 mm.

Figure 30 – Displacement sensor used during test

The sensors are all connected to a conversion device that turns the analogue signal into readable values. From this device the values are sent the main computer on which all the values are collected.

Oven camera
During testing the set-up is closed off as much as possible. It is therefore difficult to see what happens inside the oven during the test. Apart from the displacement, smoke and reflection of flames through the glass nothing can be seen on the outside. To be able to analyse what happens inside the oven Efectis has lent us their oven camera. This camera is a liquid cooled camera able of withstanding the high temperatures that occur during the test.

The difficulty of the oven camera is that is has a limited scope. It is therefore placed underneath the middle beam at the side of one of the supports to have a view of all three beams. This does result in an image of just half a beam. Since the beams are symmetric half should be sufficient.
Oven camera footage is available for test 1, 2 and 3. During test 4 the oven camera at Efectis was already in use.

Video recording
The development of the test is recorded on the outside using a number of cameras. Two cameras are set up that document the test from start to end from two slightly different angles.
A Ricoh WG-M1 digital action camera is placed above and just to the side of the set-up showing a close-range image of the test. Due to the height at which the camera is placed, the starting time of the test is somewhat difficult to pinpoint.
At a distance and in length of the beams, a Canon EOS 550D single lens reflex camera records the test. As for the action camera, the Canon cannot see the test time unfortunately. Therefore, a slight wave to the camera is done to indicate that a test has started.
On the other side of the test set-up on a service platform directly beside the test, close up footage is taken during the test. This is a combination of photos and short videos of interesting observations. These images are taken in the time available between necessary service to the set-up. These images do not form a complete story of the tests. This footage may be useful in the later analysis of the observations.
All footage is in the possession of the author and Dr. Louter.

Test Set-up

The glass beams tested are mounted in a testing rig designed specifically for 3 glass beams loaded in a 4-point bending situation above the fire furnace. The rig is based on the test rig used by Louter during similar fire resistance tests at EMPA. Figure 31 shows a schematic representation and a large version is available in the attachements. The rig is built inside an OR-frame to easily lift the rig on and off the oven.

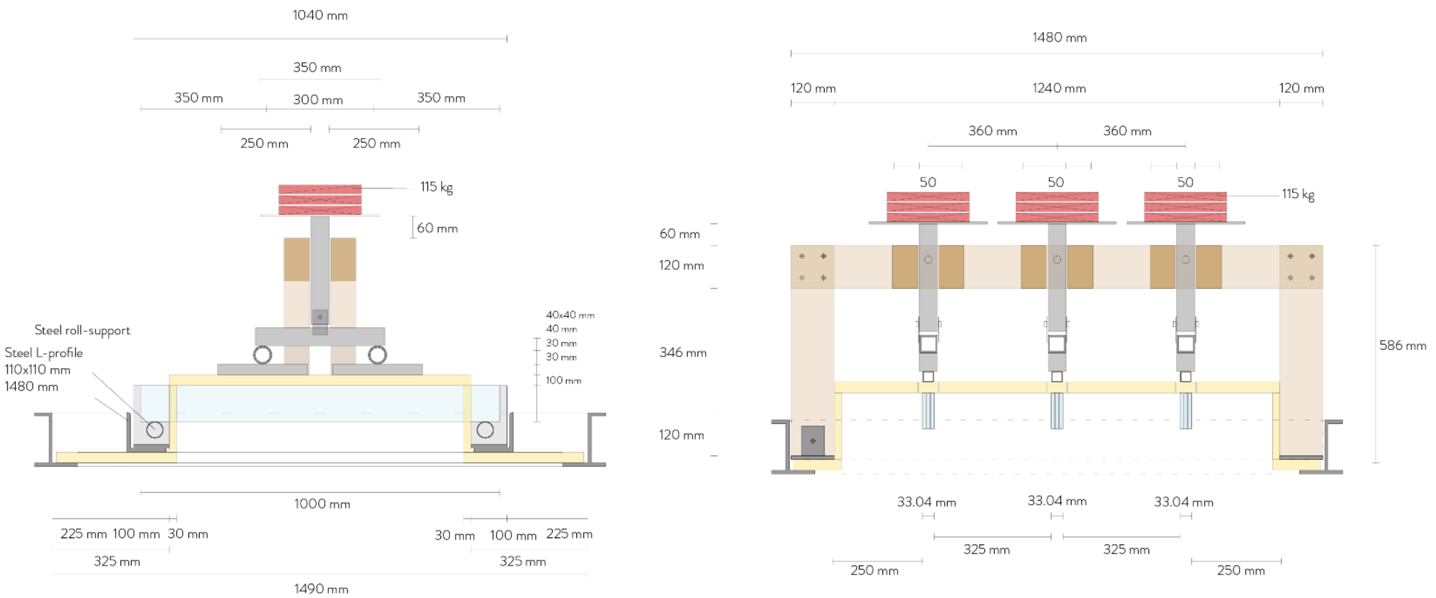


Figure 31 – Longitudinal section of the test set-up showing 3 beams positioned above the oven.

The testing rig is divided into cold and hot parts. The cold parts are shielded from the oven heating, while the hot parts are directly heated and inside the oven. To ensure the temperature difference a barrier is created by building a heat protective layer of Promatect fire protective panels.

During testing the beam supports are on the cold side of the rig while the centre of the beam is on the hot side, this is realised by a layer of vertical Promatect panels in front of the supports, perpendicular to the glass beam. The panels are continued across the glass beam to create a Promatect box protecting the cold side of the test set-up.

The fire protective panels spanning across the length of the beams are interrupted to allow for vertical displacement during testing. To cover the glass beams narrow panels approximately 50 mm span glass beam. These narrow panels are interrupted in the middle to allow for the bending behaviour of the glass beam.

A wooden frame spans over the glass beams supporting the 4-point-bending set-up. Between the paralel wooden beams slots of 54mm x 54 mm are realised through which the load resting on top of the glass beams can slide down. The loading set can move a maximum of 60 mm in the vertical direction, ensuring to load the beam untill full failure, while preventing to drop fully into the hot oven.

On top of the loading-set a steel plate offers room to place the prefered load. The wooden frame with loading-set is placed inside the OR-frame.

Figure 34 – Build up of the wooden portal spanning the oven

Figure 35 – Placement of the steel 4 point bending loading set

After sliding the top of the loading set into the wooden frame a bolt fixing the bottom to the top. The bolt connects the two parts in the vertical direction while allowing for rotation. To follow the deformation of the beam 2 extra rotation points are created by welding circular tubes to a rectangular section. The rotational point is situated between the circular tube and the smaller rectangular tubes that rest on top of the glass beams, this connection is made by two small loosely fixed bolts allowing for rotation.

Figure 32 – Promatect panels are placed underneath the set-up to shield from heat

Figure 33 - The promatect box is built up between the supports

The glass beams are supported on either side by a set of roll supports. The supports are welded into place on an L-profiled steel beam, fitted inside the OR-frame. To align the supports and the loading sets a dummy wooden beam is inserted.

As can be seen in figure 33 and 34 white Promatect panels are placed underneath to protect the wooden frame and the L-profiled beam from direct heating of the fire furnace. These fire protective panels are continued on the inside of the supports starting to build an insulating box around the glass beams. After each test the panels are checked if they can be reused for the next test. Promatect panels are developed to withstand a fire loading of at least 4 hours. Therefor, multiple test of should be possible with one set. In the end two sets of Promatect panels have used during 4 tests.

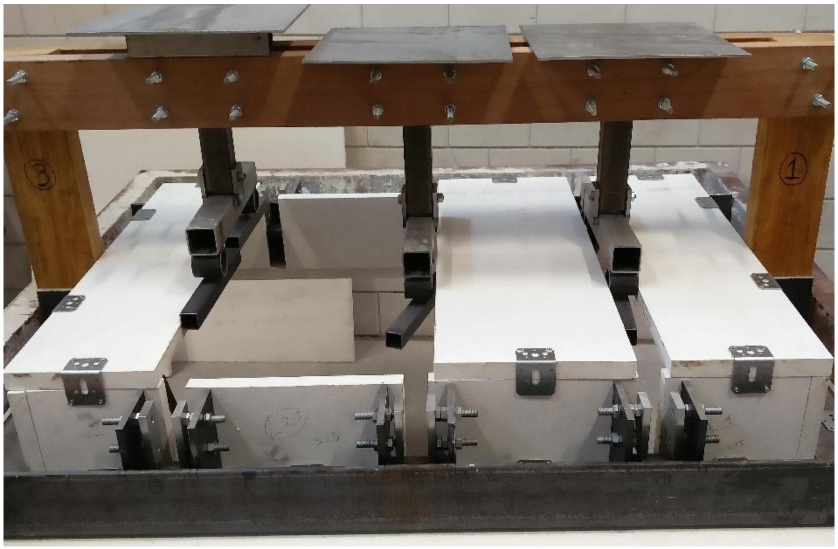


Figure 36 – Placement of the top Promatect panels with room remaining for the beams

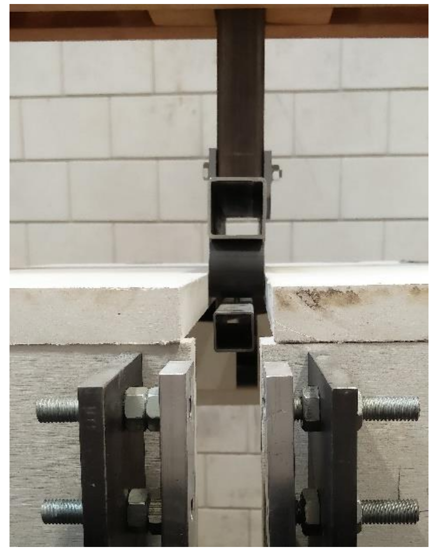


Figure 37 – Tolerance for displacement of loading set

The fire protective panels are fixed to each other with steel corners screwed to the panel. As can be seen in figure 38 it is important to allow for the loading set to drop through the fire protective panels to enable for the maximum deflection of 60 mm. This same figure shows the clamping system fixing the glass beams in place while allowing for roll in case of deformation or failure.

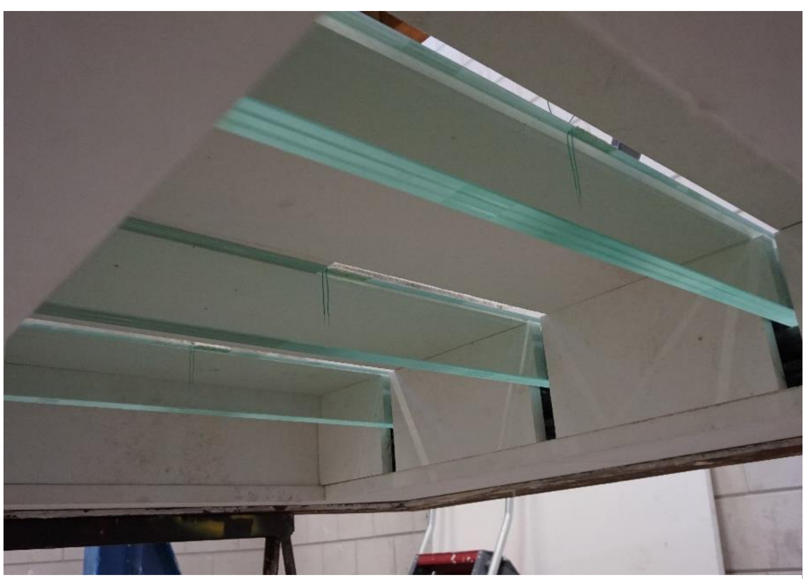


Figure 39 – 3 Glass laminated beams placed in the test set-up

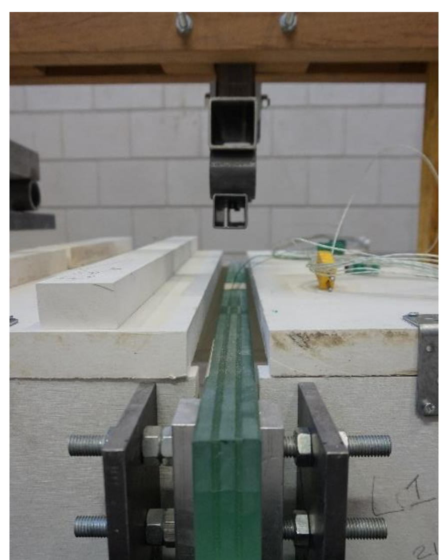


Figure 38 – Clamping of the glass beam at supports

The next step in assembly of the test set-up is placing the glass beams onto their supports. Care is taken not damage the glass when placing in the steel and aliminium supports. When in place an integrated clamping system on the side of the glass fastens the beam in place.

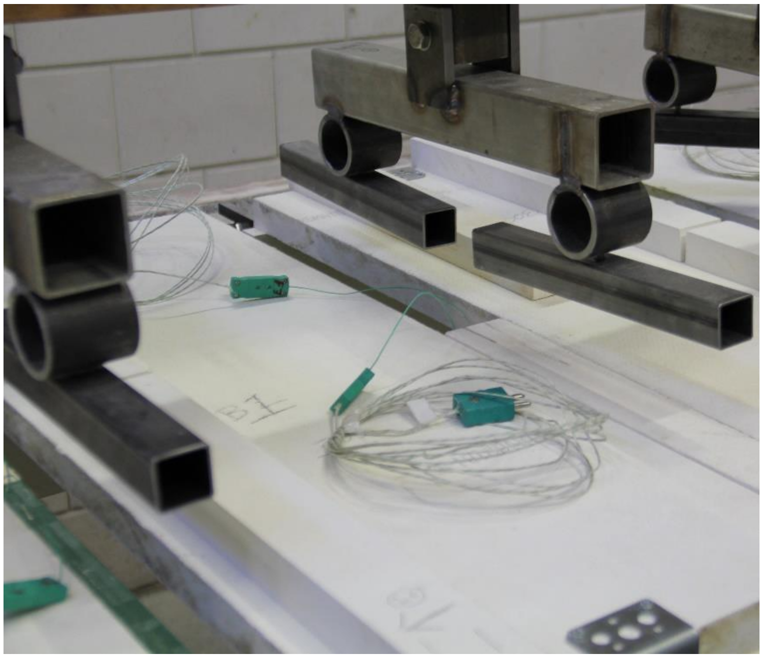


Figure 41 – Connecting of the thermocouple K extension cables

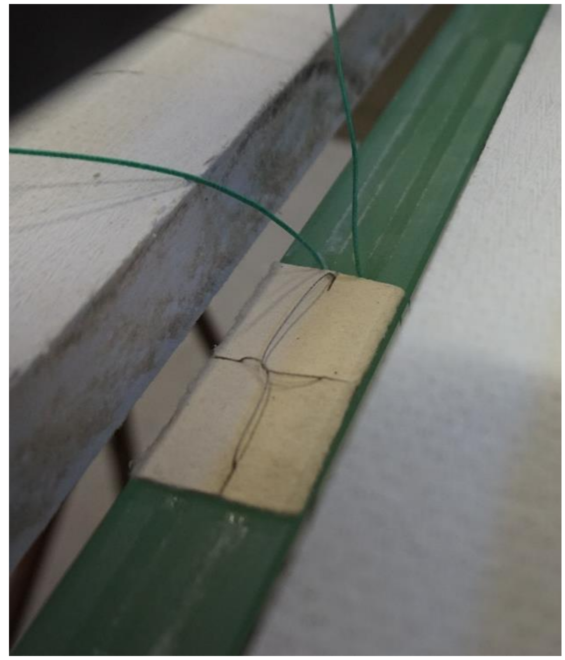


Figure 40 – Attatchment for the displacement cable

The thermocouples laminated inside the interlayers come out of the top of the beam, these small wires come up between the two narrow Promatect panels. The thermocouple wires are connected to small thermocouple type K plugs to extend the rather short wires with larger thermocouple K wires.

Next to the thermocouple wires from the beam a connection is glued into place, this plate will be attatched to a displacement measuring device. This is one of the two locations from which the displacement of each beam is measured.

After attatching the thermocouples plugs, the set-up can be closed of with the Promatect panels. To close off the possible heat leakage and unwanted heating of the supports the remaining openings are closed off using a few pieces of glass fibre insulation.

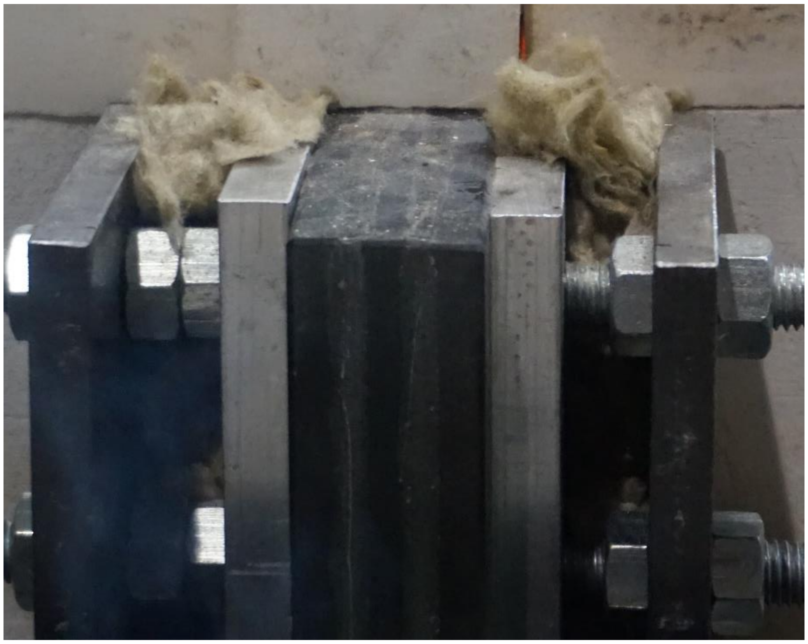


Figure 42 – Glass fibre mineral wool to close of any remaining gaps

Figure 43 – Glass fibre mineral wool underneath the beam to close of the set-up and leave room for displacement

For test 1,2 and 4 each glass beams is staticly loaded with a combined load of 115kg , 106 kg of lab weights and the loading set weighing 9.3 kg each. Test 3 uses a total combined load of 250 kg per glass beam.

The second value of displacement is measured by recording the displacement of the set of weights. This can be seen in the following figure. The measuring device is suspended above the weight and attatched to the weights with a small cable.

Figure 44 – The displacement sensors are attached to the loadcase which rests on top of the glass beams

As a final step the thermocouples, displacement devices and the oven camera are connected to the computer. The computer has a program written by Efectis to combine all the data acquired during testing, at the start of each test all the values are set to zero to calibrate the values retrieved.

Figure 45 – The monitoring computer at Efectis that registers all data during the test.

Experimental testing and results

In former research performed by Louter (Louter & Nussbaumer, 2016), glass laminated beams have been tested above a fire furnace at the research facility of EMPA in Switzerland. This test, as described in the literature study above, tested laminated glass beams in a 4 point bending set-up under fire loading. This test showed that glass laminated beams have the potential to withstand fire loading as set by EN13501-2 for a significant period of time.

The results from the test may however have been favoured by the set-up of the beams. The top 3 centimetres of the beam were protected from fire loading which could have had influenced the failure time of the beams. The glass and the according interlayer may have remained relatively cool compared to the area that was fully heated. To find out how much effect this beam set-up could have had a follow up test has been done.

The beams were placed in the test set-up as described in the corresponding chapter after which the test set-up was placed on top of the fire furnace.

Each test is documented using measurement devices as well as camera equipment. Four separate camera's captured the test from different angles, one of these is an oven camera supplied by Efectis. The oven camera was placed on the left side of the oven underneath the supported side of the beam and facing the other support. This allowed to see the 3 beams and behaviour underneath the beam and inside the oven. The other camera's documented the test from a distance.

Test #1 & #2

In order to get a good understanding of the effect of the protected 3 centimetres of the beam, the test set-up used by Louter is re-created according to the data stated in (C. Louter & Nussbaumer, 2016; Nodehi, 2016). In this test the 3 beams will be fully loaded on 3 sides of the beam. In figure 47, a section of both setups can be seen. The difference in beam set-up is the placement of fire protective Promatect panels placed on top or on the side of the glass beam. During the experiment the beams are loaded with a combined static load of 115 kg, similar to the test at EMPA.

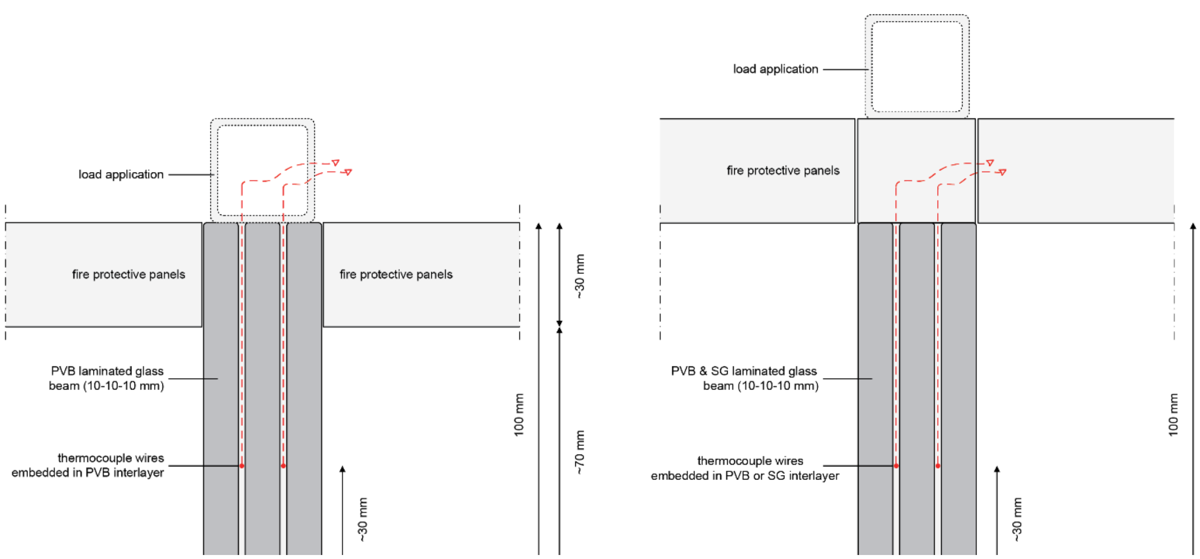


Figure 46 - Beam section comparing the EMPA test & the Efectis Test
Source: Based on work by Dr. C Louter

To be able to accurately determine the difference in behaviour between the two test set-ups, 6 different beams are tested. From the EMPA test, data is available to compared the outcome of this test. The beams are 6 beams that differ in composition, PVB or SentryGlas interlayer and 3 variants of glass.

Load 115 kg	PVB Annealed	PVB Heat Strengthened	PVB Fully Tempered	SentryGlas Annealed	SentryGlas Heat Strengthened	SentryGlas Fully Tempered
Test # 1	Pos 1	Pos 2		Pos 3		
Test # 2			Pos 3		Pos 1	Pos 2

Table 6 - Beam arrangement

The glass beams were arranged according to the predicted failure time. The three beams expected to fail quicker were placed together and the beams with an expected higher resistance. Table 6 shows the beams placed in each test with the corresponding position in the test set-up.

Test #1

The beams tested during the first test were beams with lower expected failure times. The expected

Figure 47 – Image of the glass beams and test set-up during test 1 – Beam 3 has failed

failure times are the results of the tests at EMPA. According to the conclusions of Louter a difference in thermal treatment seems to define the order of failure. This test therefore the first test places 2 annealed and one heat strengthened glass beam in the set-up.

Observation during test #1

Test #1 - 115 kg

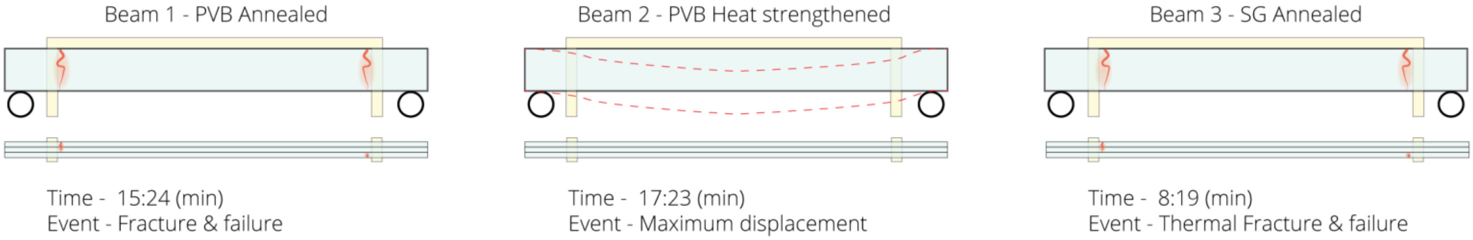


Figure 48 – Graphic representation of test 1 showing the method of failure and corresponding times

The first test is not fully documented on the oven camera unfortunately. The oven camera registers the test 4 minutes and 20 seconds into the test. This has been checked with video from other camera's and refereneced to the failure of the beam. The exact and full observations with corresponding stills from the oven camera are documented in the appendix.

Directly after the start of the test the temperature in the oven quickly increases and reaches temperatures of above 400 degrees in the first two minutes. The test set-up with all the fire protective panels and wood portal slowly heat up releasing moisture contained in the panels, this produces some steam, not to be confused with smoke in a later moment in the test.

After just over 5 minutes into the test the oven camera registers a slight change in the interlayer, the reflectivity and light absorbtance of the layer becomes dull and loses it's translucense. Half a minute later(5.47min) the first drop of PVB from beam #2 ignites underneath the beam, closely followed by beam #1 (6.40min). The flames from the interlayer slowly increase in intensity and size with the increase in temperature. The flames build up to rapid and large flames filling the image of the oven camera. The SentryGlas interlayer on the other hand, from beam #3, does not ignite untill 2 minutes later (8.52min) and after failure of the beam.

Figure 49 – Failure through thermal fracture of bema 3

At exactly 8 minutes into the test on of the glass panes in beam #3 crack due to thermal fracture, followed by collapse of the beam(8.19min) under the applied load. The fracture occurs at the side of the beam near the vertical fire Promatect panels closing off the set-up. Two panes crack one side of the set-up and the third pane cracks on the opposite side, resulting in a scissor motion during failure. The annealed glass beam with sentryglas interlayer fractures with a clean single continuous crack from top to bottom as would be expected from annealed glass. During failure the beam slowly slides down due to the softened interlayer between the glass. No flames occur at the moment of failure.

During the period of burning interlayer the glass seems stable and remains solid. This is also the case for the already fractured and failed #3 beam which is lodged inside the oven, the glass pane is still visible on the oven camera.

After another 8 minutes into the test(16.16min) the glass of beam #3 has heated up to a point that the glass has softned and it starts to sag under its own weight into the oven. The other two beams remain stable with glass that has not become soft. After a certain time period the interlayer seems to have burned up and the flames start to decrease in intensity and size.

Figure 50 – Failure through thermal fracture of beam 1

At 15 minutes and 24 seconds into the test, beam #1 can be seen to collapse on the oven camera. This is the result of sudden glass fracture in beam #1. There is no warning before fracture and the beam drops rapidly. The beam is an annealed PVB laminated glass beam, the fracture pattern as can be seen in figure 51 is very similar to the break pattern of beam #3 also annealed glass. The fracture occurs at the vertical fire protective panels on either side.

The last remaining beam, beam #2, resists the heat from the fire furnace for 17 minutes and 20 seconds after which the displacement measured determines a failure based on the increased rate of displacement. However the displacement measured is not yet visible on the oven camera. The

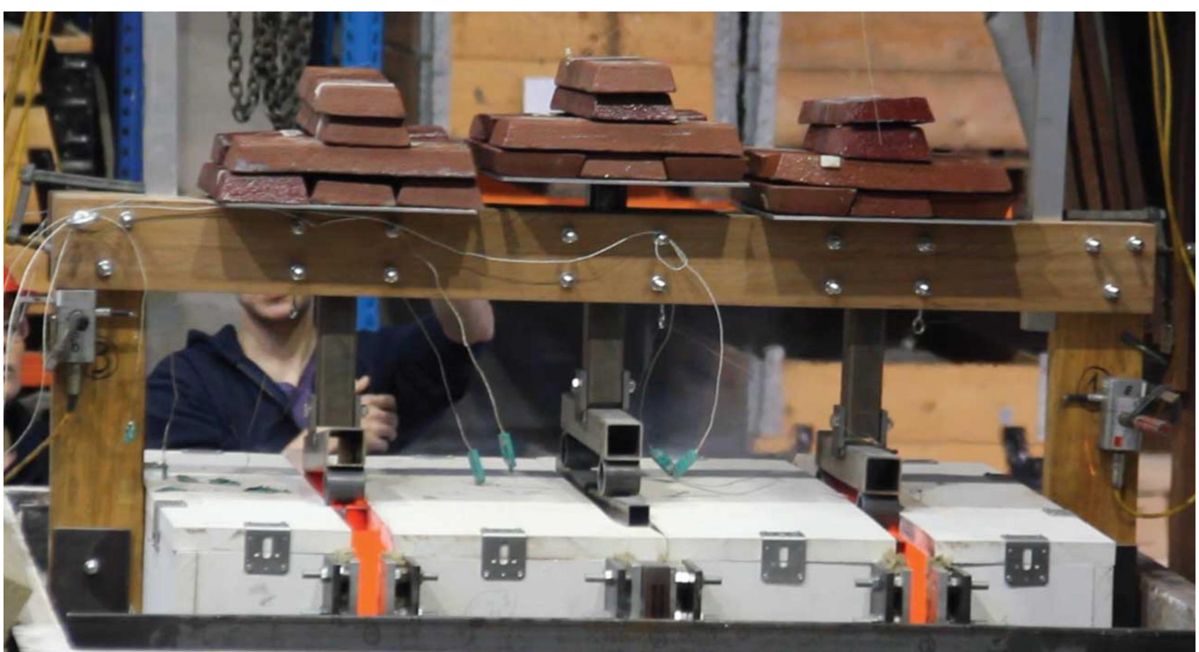


Figure 51 – Image of the test set-up showing the start of the displacement of beam 2 with slight difference visible between the promatect panels

continued heating slowly weakens the structural capacity of the glass untill at 19.18min the beam can be seen to displace. The displacement measured can be seen on the camera capturing the test on the outside, the displacement seen on this footage starts just after the 17 minutes and 20 seconds.

The beam reaches the maximum displacement of the test set-up 19 minutes and 50 seconds into the test. However the beam does not continue to sag. The displacement that occurs is the result of the loadcase of 115 kg resting on top. After reaching the maximum displacement the beam remains in this curved shape.
During the last minutes of the test the laminated glass panes displace lateraly and away from each other. In the middle section of the beam the interlayer has completely burned up and decomposed the laminate allowing the glass to sag verticaly as well as lateraly. This is clearly visible after the test, the beam remains in the set-up and cools down in it's displaced form. If you compare the remaining laminate inside the supports with the middle of the beam, the distance between the glass panes has become larger.

Figure 52 – The displaced beam 2 which remained in the test set-up after the test, which shows clear delamination of the 3 glass panes and no remaining interlayer between the glass.

The interesting thing is that the beam remains laminated inside the supports. The interlayer that creates the laminated between the glass panes does not fully melt, however there are bubbles from decomposition visible inside the interlayer. The temperature inside the supports does not result in delamination of the outer edge of the beam.

Results Test #1

The first test of this graduation research resulted in some interesting results. From the previous tests done at EMPA by Louter, the expectation might have been that the beams would slowly sag after a certain amount of time. This was only the case for one of the beams, the PVB heat strengthened laminate. The other two beams failed during the test due to glass fracture in all three glass panes.

The choice was made to place 3 relatively weaker beams in the test set-up. The material properties, corresponding to various thermal treatment, made the beams more prone to thermal fracture. The beams that failed because of fracture were laminated using annealed glass. Annealed glass has a thermal fracture resistance to a temperature difference of approximately 40 degrees Celsius compared to 100 degrees Celsius for heat strengthened glass. Therefore, there is a possibility of thermal fracture during the first steep temperature increase of the standard fire curve as stated by NEN EN 13501-2. Within a matter of minutes, the temperature climbs above 400 degrees Celsius.

What is interesting is that beam #1, the PVB annealed glass beam, failed at a much later stage and not during the rapid temperature increase. Since both beams show the same failure pattern and in the same location it may still be a thermal fracture. However, the failure in this case may have had a different cause than beam #3 such as a slight damage to the glass surface that in time caused the failure. However, since only the deformation and the temperature is measured in combination with the footage of the test, it is not possible to determine the exact reason for a fracture.

Table 7 – Results and observations of test 1

Test #1	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	First flame	Start Temp.
PVB Annealed	2	Jelle	Test 1	x	AN PVB - pos 1	115 kg	Yes	Fracture (15min)	142 C	12.27
PVB Heat strengthened	4	Jelle	Test 1	x	HS PVB - pos 2	115 kg	NO		152 C	12.43
SG Annealed	11	Jelle	Test 1	x	AN SG - pos 3	115 kg	Yes	Fracture(8min)	250 C	12.47

In the table above, table 7 the general observation and test set-up are described. The table below mentions the failure of the beams according to the criteria set by NEN EN 1363-1. The rate of deflection or max increase is set to 0.94 mm/min based on the dimensions of the beam. The maximum deflection is set to 21.16 mm. For each beam the time and corresponding interlayer temperature is listed. As can be seen in the table, both annealed beams failed before reaching the maximum deflection. The heat strengthened beam exceeded the maximum rate of deflection before exceeding the maximum deflection.

Table 8 – Results of failure times

PVB Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
PVB Annealed	2	14.89	513.05	x	x
PVB Heat strengthened	4	17.23	599.20	19.56	661.67
SG Annealed	11	7.81	219.71	x	x

The observations during the test show that the interlayers soften before the glass. The first interlayer to soften is the PVB interlayer, with the first flame on the underside at an interlayer temperature of 142 Celsius in the annealed laminate and at 152 Celsius in the heat strengthened laminate.

During the failure of the annealed glass beam with SentryGlas interlayer, the interlayer is unable to maintain the composite function due to the elevated temperature. The three glass panes were seen to slide apart, the interlayer is unable to withstand the shear stresses resulting the failed glass panes. The SentryGlas interlayer starts to burn at a later moment than the PVB interlayer. The temperature measured was approximately 250 Celsius.

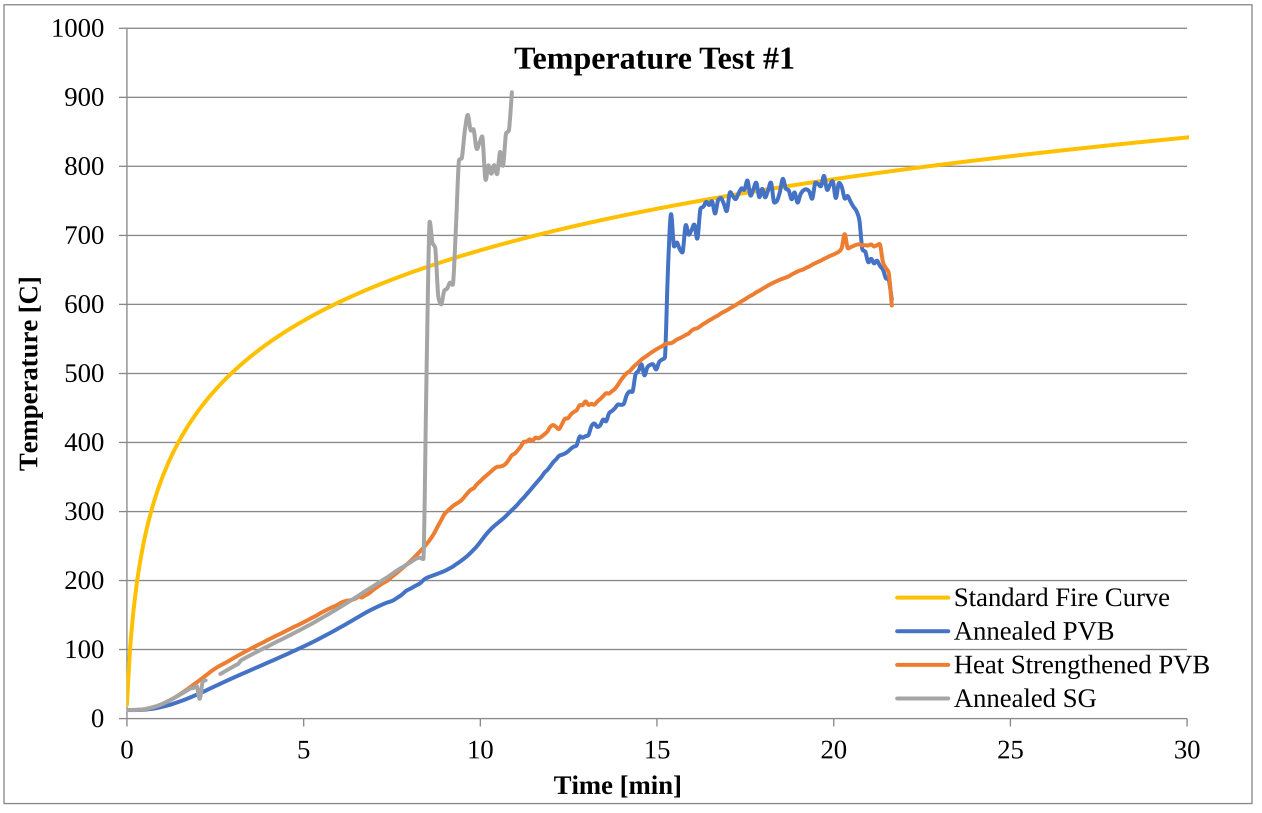


Figure 53 - Thermocouple temperature readings of the beams in test 1 - Annealed PVB, Heat Strengthened PVB and Annealed SentryGlas

Temperature-Time Curve

The thermocouple readings from the test are plot in the figure above. What we can see in first glance is the moment at which both annealed beams fail due to fracture. The steep and almost vertical rise in temperature of both temperature curves approximates the temperature of the fire furnace.

The temperature curve can be devided into three segments. The beams all show a small delay before the temperature starts to rise. In the very first minutes the temperature stays almost the same before the increase in temperature heats the area of the embedded thermocouples in the interlayer.

The increase in temperature, in the early start of the test is the second segment that is visible in the temperature curve. The curve shows a gradual increase in temperature for all three beams and all with approximately the same incline. Just before the 250 degrees Celsius, the temperature of the PVB interlayer in the annealed and heat strengthened beam shows a sharp increase in heating. At this same temperature the SentryGlas annealed beam fails.

At this moment the PVB interlayer has dripped out on the underside of the beam for a few minutes. The interlayer around the laminated thermocouples will have softened aswell, possibly exposing the end of the thermocouple to more direct heating of the oven. The temperature curve for the interlayer shows small temperature peaks which may be caused by the flames created by the burning interlayer.

The end of the test is visible in the temperature curve, showing a decrease at approximately 20 minutes.

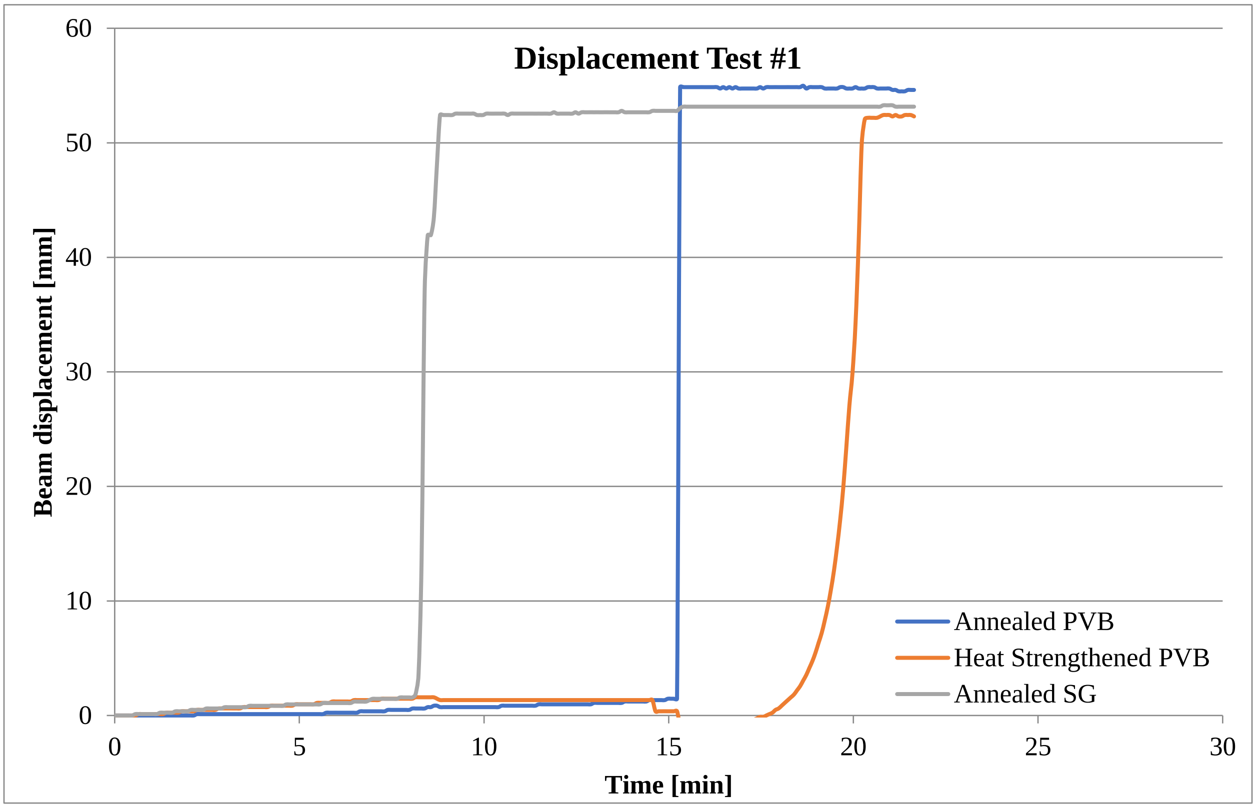


Figure 54 – Displacement readings of the beams in test 1 – Annealed PVB, Heat strengthened PVB and Annealed SentryGlas

Displacement-Time curve

The displacement of the glass beams is measured at two reference points in the test set-up. One located in the middle of the beam on top and the other point is the measurement of the displaced load resting on top of the beam.

During the analysis, the displacement data measured directly on top of the glass beam was not suitable. The glued connection between the displacement cable and the glass beam detached at a certain point during testing. Therefore the displacement seen in the figure above is the displacement recorded of the resting load.

When plotted the displacement of the two fractured annealed beams shows an abrupt and sudden displacement, which reaches the maximum displacement almost immediately. The heat strengthened beam on the other hand shows a gradual increase of the displacement resulting from the decreased material strength of glass at high temperature. The rate at which the beam displaces increases over time with added heat. After reaching the maximum displacement, no further displacement is possible. In the displacement curve of the heat strengthened beam a slight dip below 0 is visible. This is not an actual displacement of the beam, rather a slight adjustment in the cable or a slight error in the displacement sensor.

Test #2

After the successful first test, the remaining three beams with expected longer time to failure are tested. A slight adjustment is made to the test set-up due to the melting of the thermocouple plugs after failure of a beams. Due to the heat escaping from the remaining opening the plugs would melt. For the second test the thermocouple plugs were placed inside two stacked mats of glass fibre insulation to guard them from direct heating.

The beams are three thermally treated beams, two with SentryGlas interlayers and one with PVB interlayers. The load of 115 kg is the same as in test #1 and the test performed by Louter.

Table 9 – Beam arrangement

Load 115 kg	PVB Annealed	PVB Heat Strengthened	PVB Fully Tempered	SentryGlas Annealed	SentryGlas Heat Strengthened	SentryGlas Fully Tempered
Test # 1	Pos 1	Pos 2		Pos 3		
Test # 2			Pos 3		Pos 1	Pos 2

Figure 55 – Image showing the test se-up during test 2 showing 3 stable beams. The thermocouples are protected from heat with mineral wool

Observation during test #2

Test #2 - 115 kg

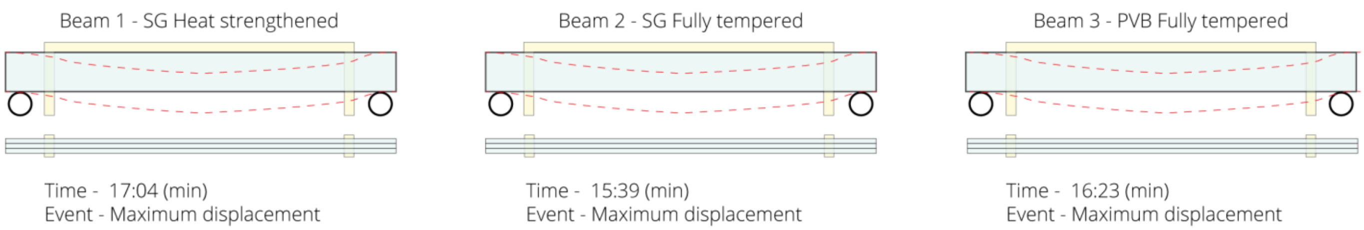


Figure 56 - Graphic representation of test 2 showing the method of failure and corresponding times

In the beginning of the test the effect of using a glass beam is visible in the form of daylight transmitted through the beams into the oven. This soon changes when the heating of the oven starts to affect the underside of the interlayer. The light transmittance starts to decrease through the interlayers, showing a difference with the glass.

After only 4 minutes the PVB interlayer of beam #3 ignites creating the first visible flame. The flames underneath beam #3 slowly start to increase in amount, size and pace.

This carries on to a point(8.15min) that the flames from beam #3 reach out towards beam #2 and even ignite an interlayer drop from the decomposing SentryGlas interlayer. This however dies out immediately, probably because the temperature of the SentryGlas interlayer is not yet above the spontaneous ignition temperature.

Figure 57 – Flames of burning interlayer underneath beam 3

The flames from #3 continue to ignite the leaking interlayer of beam #2 until at 9 minutes and 40 seconds the interlayer flames become self-spawning. At this point there are no flames visible underneath beam #1 even though the beam has the same interlayer as beam #2.

The moment(10.02min) that small flames emerge under beam #1 the flames under beam #2 and #3 have become large and intense, filling the entire oven camera view with interlayer flames.

At 11 minutes the middle beam #2, starts to show signs of delamination of the glass pane facing beam #3. The interlayer on this side seems to have melted away completely while the other interlayer still forms a laminate between two glass panes. The glass pane facing beam #3 slowly deforms laterally showing a gap between the rest of the beam. This can be seen in figure 59 below.

The direction of the melting process of the interlayers becomes visible in the reflection of one of the flames during the test. Figure 1 shows beam #1 in which a slight dark curvature is visible in the glass. The interlayer decomposes from the middle bottom of the beam towards the top and sides of the beam. This probably due to the direction of the heating of the beams.

Contrary to the expectations before the test, beam #2 is the first to start deforming (14.46). The fully tempered beam starts to deform before the flames of the burning interlayer have decreased or stopped. The beam clearly starts to sag and even twist a little at almost 18 minutes into the test(17.58min). The torsion that can be seen later in the test in figure 60 may been caused by a different heating rate of the individual glass panes in beam #2, a lower temperature of the glass means a tougher material or young’s modulus and thereby giving it different mechanical properties.

Figure 58 – Delamination in beam 2 on the right hand side and a decomposition pattern visible in beam 1 on the left

Figure 59 – Deformation of all 3 beams with a slight torsion in beam 2. Flames have stopped at this point.

Figure 60 – Displaced beam which remained in set-up after test with a strong curvature. The residue on the glass is from burned up SentryGlas interlayer

Beam #3 starts to deform visibly at 18.27min followed closely by beam #1 at 19.15 and reaching their maximum deformation 2,5 minutes after the start of their deformation. Beam #1 remains in the test set-up after switching off the oven and the cooling process. The other two beams soften after maximum deformation and drop into the oven.

What can be seen from the residue on the beam is that PVB interlayer burns a lot cleaner than the SentryGlas interlayer as can be seen in the figure to the left. The PVB beam from test #1 had clean glass panes with hardly any residue, while the SG leaves white and black residue.

Results Test #2

The expected more resistant set of beams failed in result of the weakened mechanical properties of the glass. The elevated temperature softened the glass after which the beams started to displace until reaching maximum displacement. No fracture was registered in contrary to the first test.

The PVB interlayer of the fully tempered beam 3 started to burn at an early stage in the test, the internal temperature of the interlayer was just 93 degrees Celsius when the first drop ignited. The SentryGlas interlayer ignites some time later when the measured temperature of the interlayer was at respectively 273 Celsius in the heat strengthened beam and 283 Celsius in the fully tempered beam. This temperature and time differences were also registered in the previous test.

Table 10 - Results and observations of test 2

Test #2	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	First flame	Start Temp.
SG Heat strengthened	14	Jelle	Test 2	x	HS SG - pos 1	115 kg	NO		273 C	15.19
SG Fully tempered	17	Jelle	Test 2	x	FT SG - pos 2	115 kg	NO	Radiant heat effect	283 C	15.61
PVB Fully tempered	9	Jelle	Test 2	x	FT PVB - pos 3	115 kg	NO		93 C	15.65

In the table above, the general observation and test set-up are described. The table below mentions the failure of the beams according to the criteria set by NEN EN 1363-1. The rate of deflection or max increase is set to 0.94 mm/min based on the dimensions of the beam. The maximum deflection is set to 21.16 mm. For each beam the time and corresponding interlayer temperature is listed.

Table 11 - Results of failure times test 2

Test #2	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
SG Heat strengthened	14	17.04	508.50	19.45	654.58
SG Fully tempered	17	15.39	578.46	17.87	500.56
PVB Fully tempered	9	16.23	585.56	18.54	639.05

The order of failure in this test does not occur in the order of pre-stress from thermal treatment. The fully tempered beam laminated with SentryGlas (SG) interlayer fails before the heat strengthened beam with a lower pre-stress. The fully tempered (FT) beam fails in rate of displacement after 15,5 minutes, while the heat strengthened (HS) beam fails 1,5 minutes later after 17 minutes. However, if we look at the temperature of the two beam interlayers we can see a big difference between the two. The interlayer of the FT SG beam has a temperature 70 degrees higher than the HS SG interlayer which fails later and at a lower temperature.

The observation of the oven camera shows that during the test the PVB interlayer ignites early in the test. The flames produced by the PVB are located on the right-hand side of the oven, next to the FT SG beam which is placed in the middle. This may have effect on the heating process of the middle beam, mainly a one-sided effect. The radiant heating produced by the flames is absorbed by the glass and interlayer facing the FT PVB beam, increasing the heating process on this side.

After 11 minutes the glass pane of the FT SG beam facing the FT PVB beam shows a slight delamination and lateral deformation. This is again visible during the displacement of the beam, when torsional displacement takes place. Possibly due to the temperature difference in the glass panes of the beam.

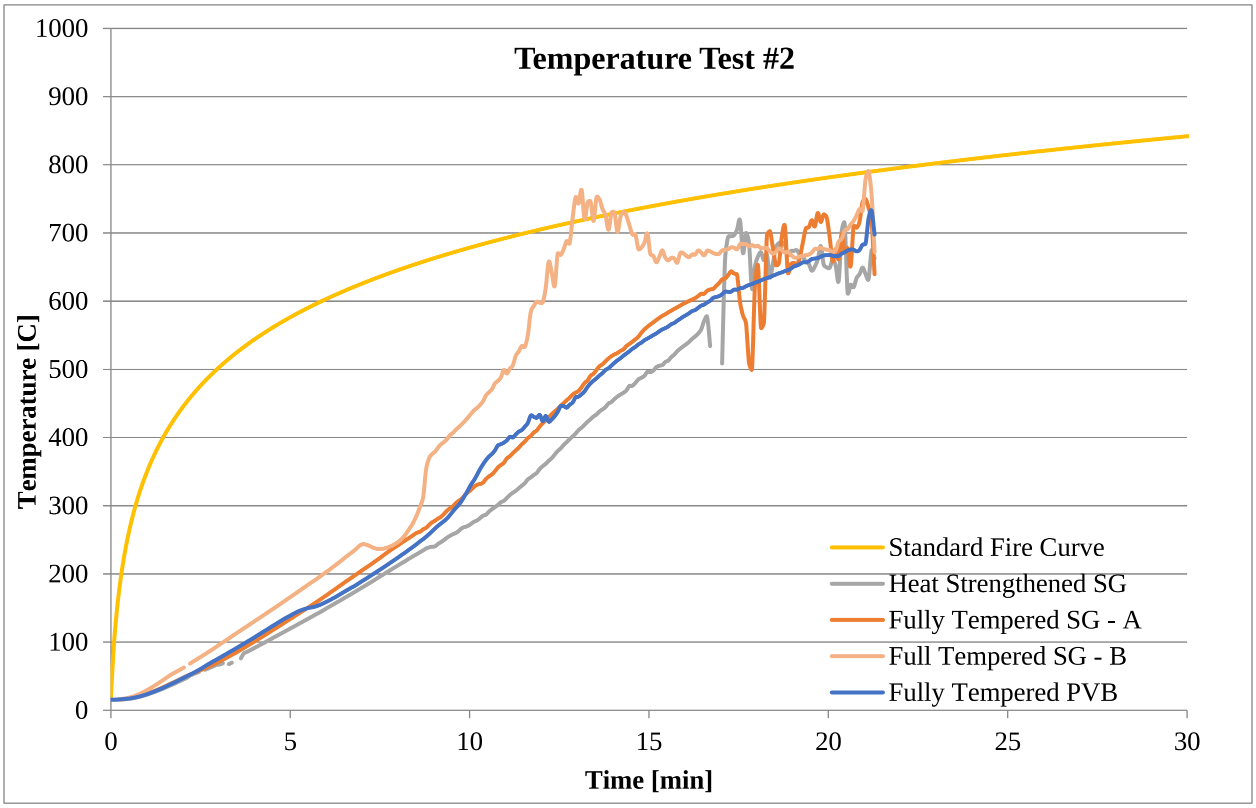


Figure 61 – Thermocouple temperature readings of test 2 – Heat strengthened Sentryglas, Fully tempered Sentryglas, Fully tempered PVB

Temperature-Time Curve

The first thing that stands out when looking at the temperature plot of test 2, is the large temperature spike of the fully tempered (FT) SG beam. The plot has two separate temperature curves for the FT SG beam since the temperature readings between the thermocouples A & B vary. As described in the observation the FT PVB beam produced flames after 4 minutes into the test. The radiant heat produced by the flames clearly affected the registered temperature of thermocouple B.

The additional spike in the FT SG-B temperature can be related to the delamination of the outer glass pane. The delamination exposes the thermocouple at which point the thermocouple does not register the interlayer beam temperatures, rather the temperatures registered are the oven temperature. The intersect with the fire curve temperature occurs around 13 minutes.

The temperature of the heat strengthened SG beam seems less affected by the flame production in the oven. The radiant heating will have some effect on the heating, however this does not lead to substantial irregularities in temperature curve. The overall temperature increase of the HS SG beam has the slowest increase compared to both FT beams. This eventually results in the latest failure of the 3 beams and a better performance.

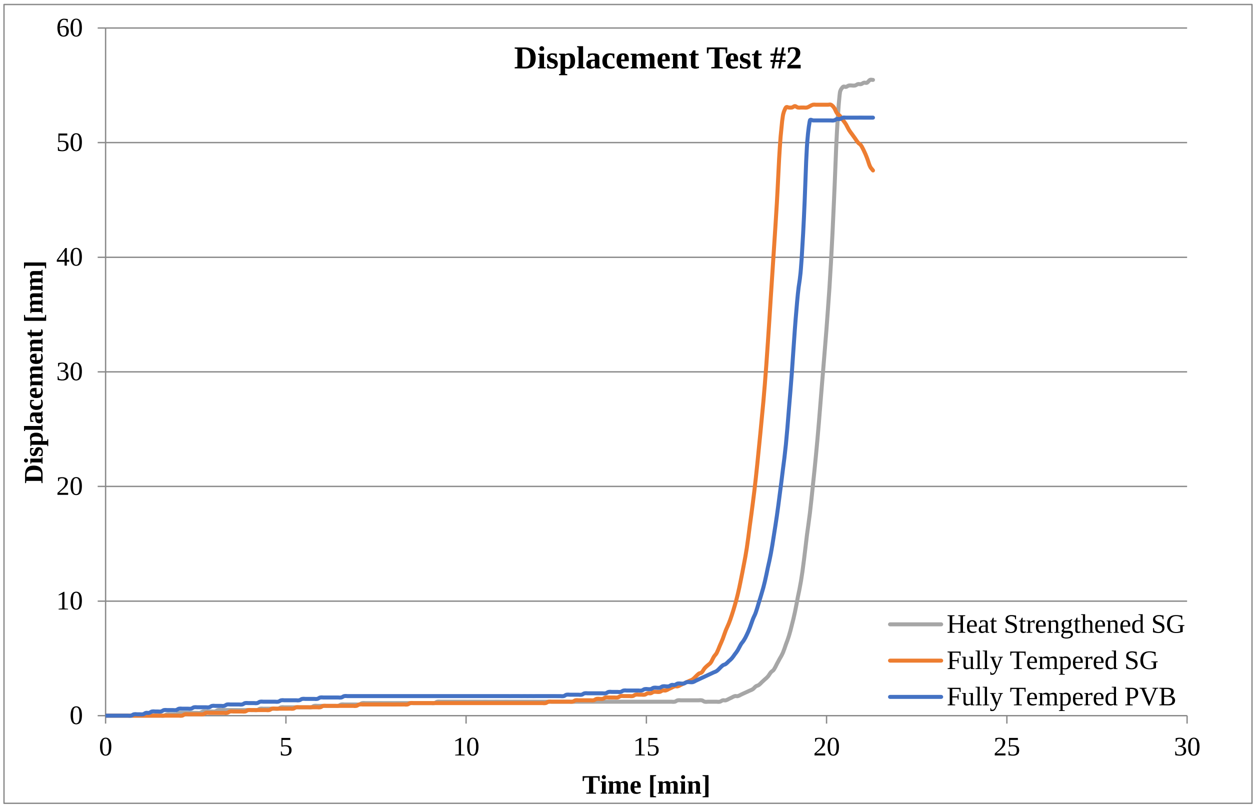


Figure 62 – Displacement readings of test 2 – Heat strengthened Sentryglas, Fully tempered Sentryglas, Fully tempered PVB

Displacement curve

The three beams in test 2 did not show any form of structural failure such as fracture. The displacement curves do not show sudden and direct failure of the beams. The results show similar trajectories for all three beams that starts to show the difference in performance approximately 15 minutes into the test. From this point on the beam deformation increases until reaching the maximum displacement.

An interesting observation in the displacement curves is that the start of the displacement of the FT PVB beam starts just after 12,5 minutes, before the FT SG beam starts to deform. The displacement of the FT SG beam however surpasses the total displacement of the FT PVB beam a few minutes later and failing before the PVB beam.
The heat strengthened beam, which was seen to have the lower temperature increase during the test, clearly shows the latest displacement of the three beams.

Test #3

The next step in the testing process was to investigate if the 115kg as applied by Louter in the testing at EMPA had a favourable outcome on the failure time of the glass beams. Louter stated that “The applied load of about 115 kg is relatively low and generates a tensile bending stress of only about 5 MPa.” The reason behind the relatively low load case was the porous structure of the fire furnace on which the beams were supported.

In the test set-up for this research the supports were placed inside two L-shaped beams that transferred the load of the glass beams and the load case to the outer concrete wall of the oven. The inner porous wall of the oven was therefore not loaded, giving the possibility to increase the load case on top of the beams. This allowed for an increased load of 250 kg on top of each beam. The increased load can be seen in the figure below. The tensile bending stress is now increased to approximately 11 MPa.

During this test a full set of SentryGlas beams was used. The thermal treatment and position can be seen in the table below.

Table 12 – Beam placement test 3

Load 250 kg	PVB Annealed	PVB Heat Strengthened	PVB Fully Tempered	SentryGlas Annealed	SentryGlas Heat Strengthened	SentryGlas Fully Tempered
Test # 3				Pos 2	Pos 3	Pos 1

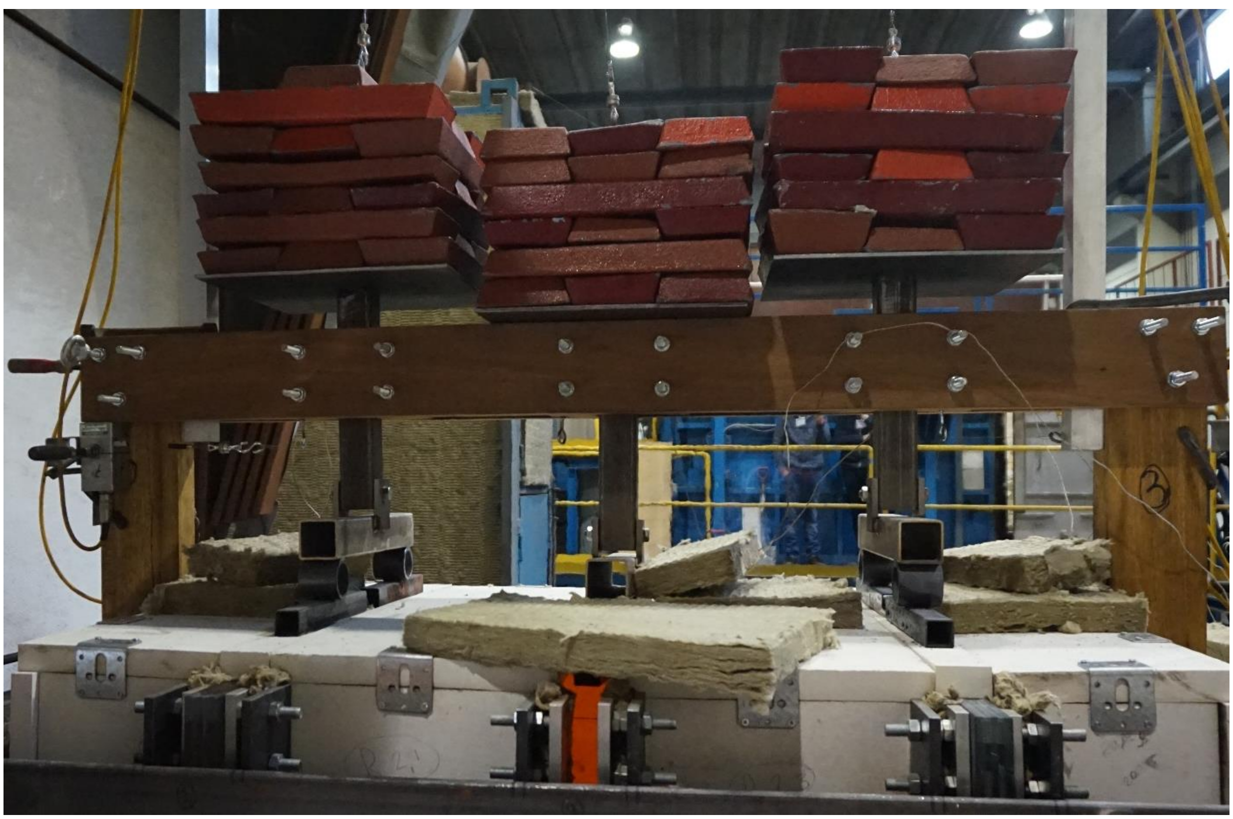


Figure 63 - Image of test #3 with increased load after failure of Annealed SentryGlas due to thermal fracture

Observation during test #3

Test #3 - 250 kg

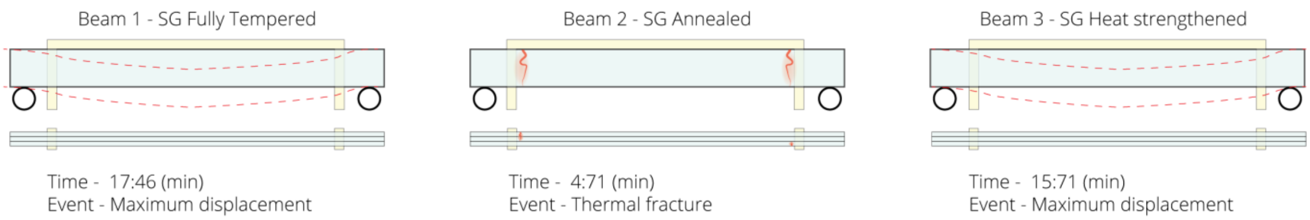


Figure 64 - Graphic representation of test 3 showing the method of failure and corresponding times

Before the start of the test, the load placed on top of the 4 point bending set-up looks a lot bigger than previous tests. The glass beams using SentryGlas interlayers are strong enough to withstand the static load of 250 kg before being placed on the oven.

Figure 65 – Image of oven camera during the first minutes showing light transmitting into the oven from outside.

The oven camera in the test starts off focussed on the light transmitting into the oven. Luckily for the observation of the rest of the test the focus slowly shifts to the inside of the oven. Four minutes into the test the light transmittance through the glass becomes minimal as the interlayer becomes affected by the rising temperature.

Beam #2 fails after just 7 minutes and 55 seconds due to thermal shock. The failure pattern is very similar to the failure of the annealed glass beam from test #1. The glass panes fracture close to the vertical promatect panel and the beam fails in a scissor like deformation as the panes slide appart. The glass panes crack on one side of the beam in a clean single vertical fracture from top to bottom. This can be seen in figure 67 , which shows two fractured glass panes that drop passed the oven camera and rotate away from the single glass pane that has cracked on the other side of the beam. Due to the slightly soft interlayer the beam slowly drops instead of dropping immediately. Another interesting observation that can be made from the failing beam is that in the SentryGlas interlayer drops have formed

Figure 66 – Failure of beam 2, showing the single vertical fracture in each beam, typical to annealed glass. The beam fails in a scissor like motion.

on the bottom edge of the glass. These drops do not ignite, due to a relatively low temperature for spontaneous ignition.

Two minutes later, the drops as seen on beam #2 can be witnessed on the underside of beam #1 and #3. This is followed by the first flame underneath beam #1 a minute later(10.51min) and another 2 minutes later(13.13min) underneath beam #3.

The intensity of the flames increases with further rise in temperature. During this period, the decomposition of the interlayer is visible in the interlayer of beam #3. This can be seen in the figure to the right. A dark burning pattern of the interlayer can be identified in between the glass panes.

Figure 67 – Beam 1 on the left shows a blackened decomposition pattern of the interlayer, the interlayer decomposes from the middle centre to the top and sides

The interlayer in both remaining beams eventually burns up completely after melting from in between the glass panes. The flames of beam #1 decreases 17 minutes and 48 seconds into the test, followed by beam #3 (19.23min).

The first deformation of beam #1 becomes visible on the oven camera after 22 minutes followed a minutes later by beam #3. However, the displacement measured on beam #1 indicates it has been slowly displacing since 15,5 minutes. This also the case for beam #3 which has slowly started to move at 17,5 minutes. After 22 minutes 30 seconds, so 30 seconds after the displacement becomes visible, beam #1 reaches its maximum displacement. The beam eventually starts to sag under its own weight due to further heating at which point beam #3 reaches the maximum displacement(24.14min). In the last shot of the oven camera beam #1 drops into the oven while #3 remains at maximum displacement, however after the camera is turned off the beam sags into the oven.

Results of Test #3

The focus of the 3rd test was to investigate the effect of an increased load case. The load case was increased from 115kg to 250 kg. The set of beams were annealed, heat strengthened and fully tempered SentryGlas beams. After the retrieving some unclear results from test 1 and 2 due to the difference in PVB and SentryGlas interlayer, the beams in test 3 all used the same interlayer combination.

During the test the annealed Sentryglas beam failed from thermal fracture after just 5 minutes. The heat strengthened (HS) and fully tempered (FT) beam failed after a standard heat and displacement process. The interlayer ignites at a much later moment during the test than what was seen in the first two tests. Unfortunately, the fracture of the AN SG beam does not give us information on the ignition of the interlayer. The two beams that can be observed on the oven camera show first flames at 10,5 minutes for the HS SG beam and 13 minutes for the FT SG beam. The temperature measured at these points are higher than previous tests. The temperature at first flame of the HS SG beam was 362 degrees Celsius and the FT SG beam 335 degrees Celsius, compared to the 250-280 degrees measured in the first two tests.

Since the interlayers started burning around the same time, the effect on the failure behaviour of the remaining beam would have been less severe as the temperature increase of the FT SG beam in test 2. Where the radiant heat from the burning PVB interlayer spiked the beam temperature.

Table 13 – Results and observations of test 3

Test #3	Beam #	Researcher	Test #	Addition	Position	Load case	Fracture	Observation	First flame	Start Temp.
SG Fully tempered	18	Jelle	Test 3	x	FT SG - pos 1	250 kg	NO		335 C	12.30
SG Annealed	12	Jelle	Test 3	x	AN SG - pos 2	250 kg	Yes	Fracture(5min)	x	12.03
SG Heat strengthened	15	Jelle	Test 3	x	HS SG - pos 3	250 kg	NO		362 C	11.92

In the table above, table 13 the general observation and test set-up are described. The table below mentions the failure of the beams according to the criteria set by NEN EN 1363-1. The rate of deflection or max increase is set to 0.94 mm/min based on the dimensions of the beam. The maximum deflection is set to 21.16 mm. For each beam the time and corresponding interlayer temperature is listed.

Table 14 – Results of failure times of test 3

Test #3	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
SG Fully tempered	18	17.46	514.92	20.29	600.48
SG Annealed	12	4.71	139.27	5.13	151.96
SG Heat strengthened	15	15.71	571.36	18.63	625.56

The failure of the AN SG beam was caused by thermal fracture. Of the three SentryGlas beams the annealed glass has the lowest thermal fracture resistance leaving it vulnerable to fracture. The fact that the annealed glass beam fractures also occurs in the first test of the graduation research. While the annealed glass beam in the EMPA test of Louter did not fracture, the two beams in this set-up both fractured. Perhaps the thermal fracture may have occurred earlier due to the increased loading, this is currently a guess for which a larger number of follow up tests would be necessary to determine.

The other two beams failed according to the rate of displacement criterium. The corresponding failure times are 15,5 minutes for the HS SG beam and 17,5 minutes for the FT SG beam. These times are familiar to the failure time witnessed in test 2. However, the order of failure is vice versa, with the FT SG beam to withstand the fire loading for a longer period of time than the HS SG. In test 2 this order was the other way around, although there is a strong possibility that the FT SG beam was strongly affected by the neighbouring PVB beam.

If only looking at the failure time of the HS SG beams from test 2 and 3, the failure time in the last test with increased loading was lower. The time difference between the two under 1,5 minutes. If the resistance has been affected by the increased loading is difficult to say.
The SG beam sees an improved failure time compared to test 2. The outcome of the second test may not be indicative for the FT SG performance, which makes it is difficult to determine if the increased load has had effect on the failure time. Ideally, the 115kg set-up would be repeated in a later stage.

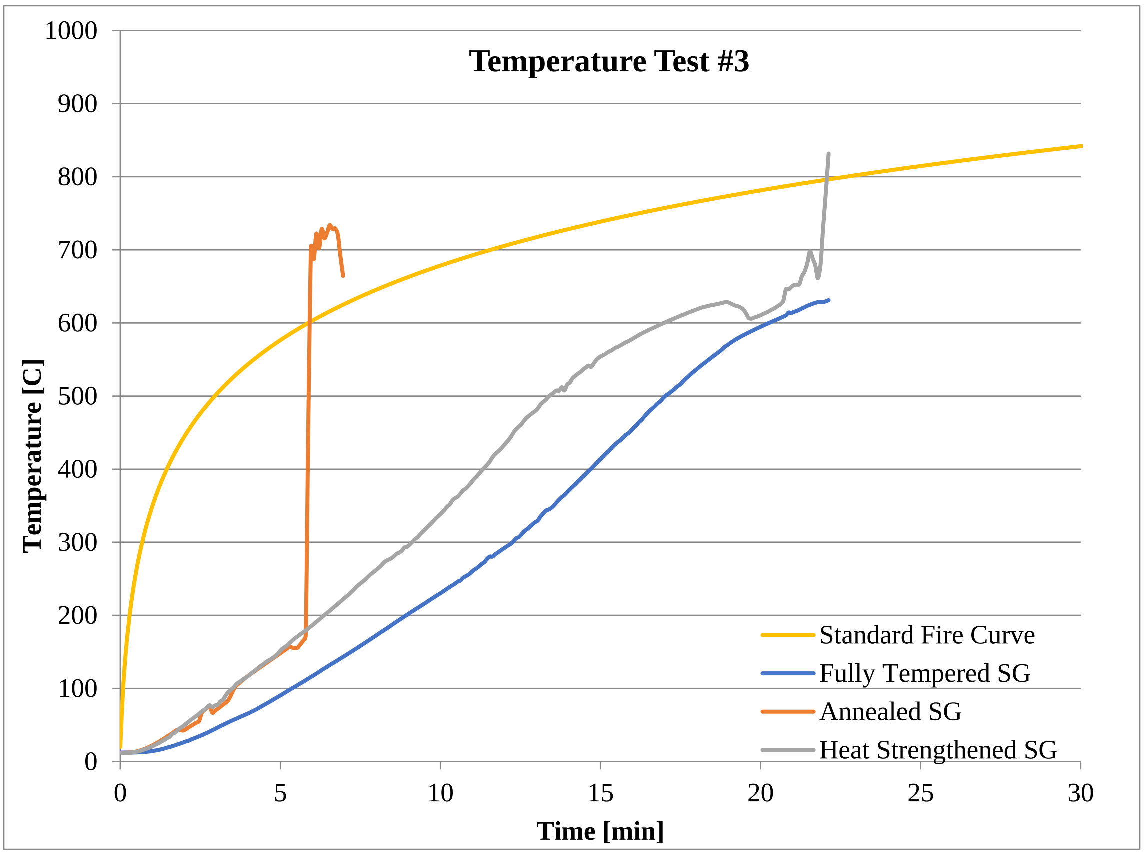


Figure 68 – Thermocouple temperature readings of test 3 – Annealed SentryGlas, Heat strengthened SentryGlas, Heat strengthened SentryGlas

Temperature-Time curve

Instead of three temperature curves that continue to the end, the AN SG beam fails fairly quickly during the third test. The temperature spike that is visible just after 5 minutes is the thermocouple wire exposed to the inside temperature of the oven after the beam has dropped into the oven.

The two remaining SentryGlas beams show a rather smooth temperature increase. The two beams however show a large difference in the rate of heating during the test. The temperature of the HS SG beam rises quicker than the FT SG beam. The heating can be seen to overlap with the AN SG beam for the first 5 minutes until it fails.
Directly from the start, the heating of FT SG beam has a different rate compared to the two other beams. The curve is seen to split from the other two beams after the first 1 to 2 minutes of the test during the rapid temperature increase of the standard fire curve.

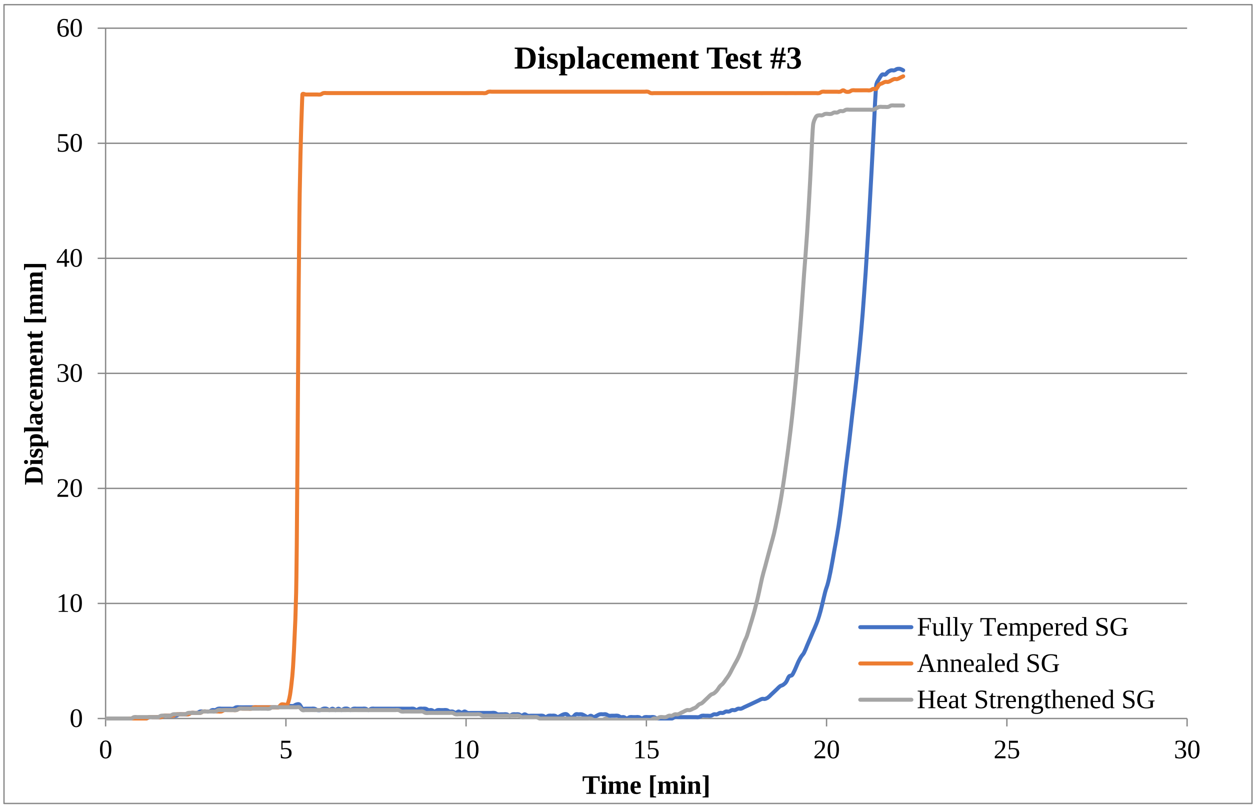


Figure 69 – Displacement readings of test 3 – Annealed SentryGlas, Heat strenghtened SentryGlas, Heat strenghtened SentryGlas

Displacement curve

The displacement values of the annealed glass beam show the distinct shape for a fractured beam. The beam undergoes a sudden and full displacement after thermal fracture. The failure of the two other beams increases gradually.

From the start of the test, a slight displacement of approximately 0.75 mm occurs in all three beams. The displacement sensors are reset to zero in the beginning of the test, the sensor is attached to the displacement cable by extending the sensor approximately 5 centimetres. During the initial heating of the oven and the set-up there is a possibility that the steel cable used elongates due to thermal expansion. If this accounts for the difference measured is unclear. Another possibility is a slight error in the sensor, however this would be approximately the same error in each sensor.

The HS SG and FT SG beams show a similar displacement curve as beams in earlier tests. During the first 10-12 minutes the beams seem stable at which point the displacement slowly occurs. The deformation of the beam slowly increases in rate until the point that the glass can no longer withstand the combination of heating and the static load case. The measured displacement is limited to the movement possible for the 4-point-bending set-up inside the test set-up. The beam is able to displace further when the strength of the glass decreases further, eventually the beam will sag and drop into the oven.

The order of failure takes place in order of thermal treatment of the beams. The beam with the highest induced pre-stress through tempering showing the highest resistance to fire loading.

Discussion of test 1,2 and 3

The tests in this graduation research were the first experience with performing fire furnace tests. The method used by Louter at EMPA seemed successful, therefore the test set-up was used as the basis for the tests. One of the main reasons was to be able to directly compare the results from this graduation research with the results from the EMPA test.
The actual building of the test set-up required more time than initially expected, this had to do with the different design of the fire furnace as well as the slight change to the placement of the fire protective panels. The test set-up eventually performed as desired during the tests and the results can compared with the EMPA test.

The choice of combining the beams with the lowest resistance and the beams with the highest resistance in the first two tests may have not been the best decision. The different behaviour of the PVB and SentryGlas interlayer has clearly had effect on the behaviour of the beams during the tests. Ideally the beams are tested individually above the fire furnace to eliminate any external influences. This is unfortunately not possible due to the limited fire furnace tests. Therefore 3 beams were placed at a distance from each other. In the third test, with the increased load of 250 kg the 3 beams was a full set of SentryGlas beams, the reason behind this had to do with the effects described above.

The varying behaviour of the beams in test 1 and 2 results in less clear results than the results at the EMPA tests. The behaviour of the beams and the corresponding failure times have to be analysed while taking in account the external influences. This makes it more difficult to draw clear and specific conclusions.

One of the conclusions that may have been affected by the less clear results is the effect of the increased load. The increase of 115 kg to 250 kg has to be evaluated using the result of the FT SG beam that underwent additional radiant heating in test 2. The failure time of the FT SG beam in test 3 shows a higher time to failure than the beam in test 2 and a better failure time than the less affected HS SG beam. However, this may have been different if the beams in test two had not undergone the radiant heating of the PVB beam. This will now remain speculation until further testing can be done.

What could have improved the conclusions is improving the number of tested beams. Increasing the number of test specimens decreases the chance and effect of external influence on the outcome of the tests. Unexpected behaviour and other irregularities during the tests now make it difficult to draw clear conclusions.

Due to the scale of the fire furnace tests it could be interesting to perform additional small-scale tests to improve the conclusions from this graduation research.

Conclusions

The series of three tests were performed on a fire furnace designed to test building elements and their fire resistance to high temperature heating. The tests continued the research into fire resistant structural laminated glass beams, initiated by Dr. Christian Louter(C. Louter & Nussbaumer, 2016). The first three tests provided a number of interesting insights. Insights into the behaviour of structural glass under fire loading and insights on the test methodology.

- The beams in all three tests did not meet the minimal requirement of a fire resistance to failure of 30 minutes set by building regulations.
- The protected top 3 centimetres in the EMPA test by Louter shows better failure times.
- The placement of different interlayer beams influenced the outcome of the first 2 tests.
- The failure of the beams seems to be in the order of the thermal treatment of the beam, as was the result in the tests performed by Louter. However, the results from the tests performed in this graduation research are not as clear as the results from the EMPA tests due to several influences.
- The FT PVB beam performed better than the HS PVB beam, which performed better and the AN PVB that fractured.
- The FT SG beam from test 3 had a later time to failure than both HS SG beams. Both annealed SG beams failed early through fracture.
- The failure time of the FT SG from test 2 was influenced by the behaviour of the PVB beam beside it, underperforming the HS SG beam in this test.
- The radiant heating of the flames had a significant heating effect on the glass and interlayer of the FT SG beam facing the flames during test 2.
- The PVB laminate starts to decompose and burn at an earlier stage than the SG laminates. This corresponds to the findings of Debuyser(Debuyser et al., 2017) and the specifications offered by DuPont(Dupont, 2018).
- The beams in the 3 tests fail at lower temperatures, than the temperatures measured at EMPA. The average measured temperature of the thermocouple at the moment of failure was 543 Celsius for the PVB beams and 566 for the SentryGlas beams. The temperatures during the EMPA test were respectively 748 Celsius for PVB and 744 for SentryGlas.
- Increased load does not seem to influence the time to failure. Perhaps when applying a more critical load on top of the beams the failure might become more sudden. Currently the failure times between test 2 and 3 are very similar, as are the displacement curves.

Finite element heat flow analysis – Diana FEA

The acquired data from experimental tests can be validated using finite element analysis or FEA. A 3D digital model is built in Diana FEA, a software package that can simulate a heat flow analysis similar to the heating process of the fire furnace used at Efectis. The 3D model is built with several components that represent the different materials in the fire test. The reason for choosing Diana is the former experience with the software package.

The model as shown in figure 1 shows half a beam. Since a beam is symetric, modelling half of the beam provides values that are representative for the whole beam. The model does not only contain the glass beam. During the test the Promatect panels that are placed on top of the beam interact with the glass beam in regards to heating and energy transfer. Therefore an element of Promatect is added on top to incorporate the effects during the heating process.

Heat flow analysis in Diana

The beam is recreated to resemble the beam from the physical tests. The different materials are described with their corresponding material properties. Since the simulation is a heat flow simulation, the material properties are temperature dependant, meaning that the material properties vary according to the temperature of the material. The temperature dependant properties of glass are obtained from literature research for glass and are added to the model. For Promatect and the interlayers values provided by manufacturers. The list of values used can be found in the appendix.

The heat flow analysis is run by the heating the beam as if it were in the fire furnace. The temperature increase is set to match the standard fire curve as described by building regulations.

The heating has to be attatched to the relevant surfaces as a boundary condition. This is the case for the surfaces heated by the standard fire curve as well as the surfaces facing outward. For the outward facing surfaces an ambient temperature is attached.

Simulation results and comparisson

When all the relevant model properties have been described the analysis can be set up. The analysis is performed in time steps of 20 seconds. This is the reason that the results in the comparisson figures are shown in seconds.

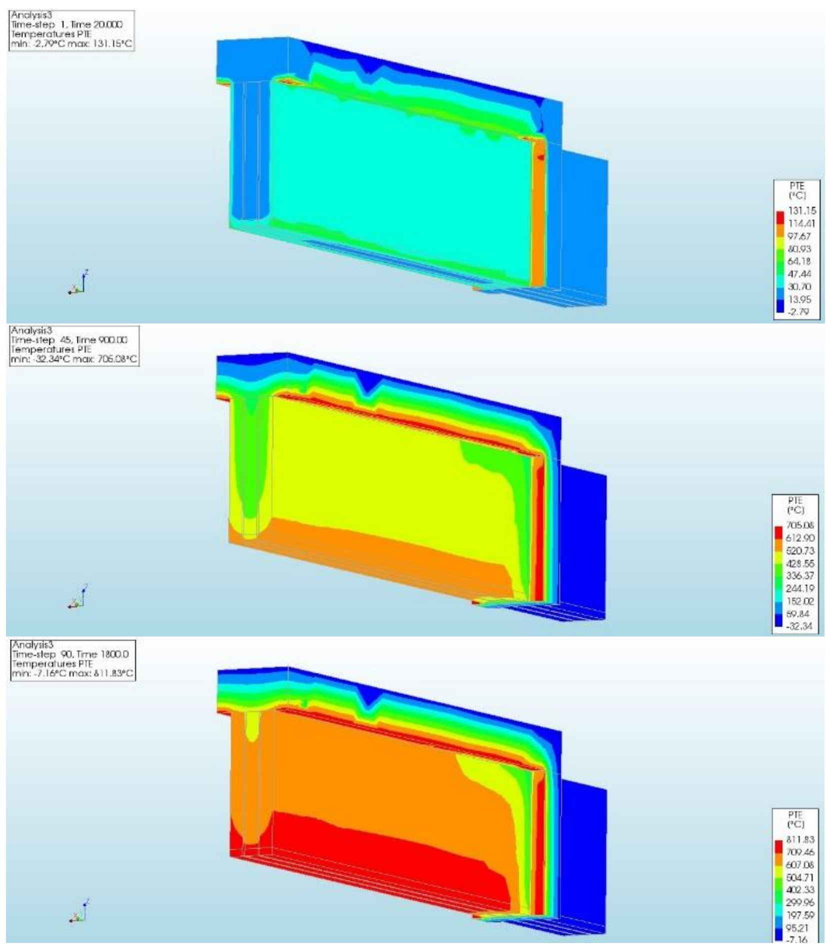


Figure 70 – Heat flow gradient produced by Diana at 3 time steps – 20 seconds, 900 seconds(15min) and 1800 seconds(30min)

The three bright coloure images show the heat flow temperature gradient as a result of the heat flow analysis. As can be seen the temperature of the glass beam heats up during time and the fire protective Promatect panels contain the heat inside the oven.

The eventual heat flow analysis is used to validate the temperature values obtained through experimental testing, the temperature values are plot in the figures below. The simulated beam is represented by three separate temperature curves namely the outer glass pane, the interlayer and the middle glass pane. The temperature value measured during the experimental testing is registered inside the interlayer of the beam, 3 centimetres from the bottom. The values from the simulation are all taken 3 centimetres from the bottom. The green line represents the standard fire curve, which is used to heat the beam in the heat flow analysis.

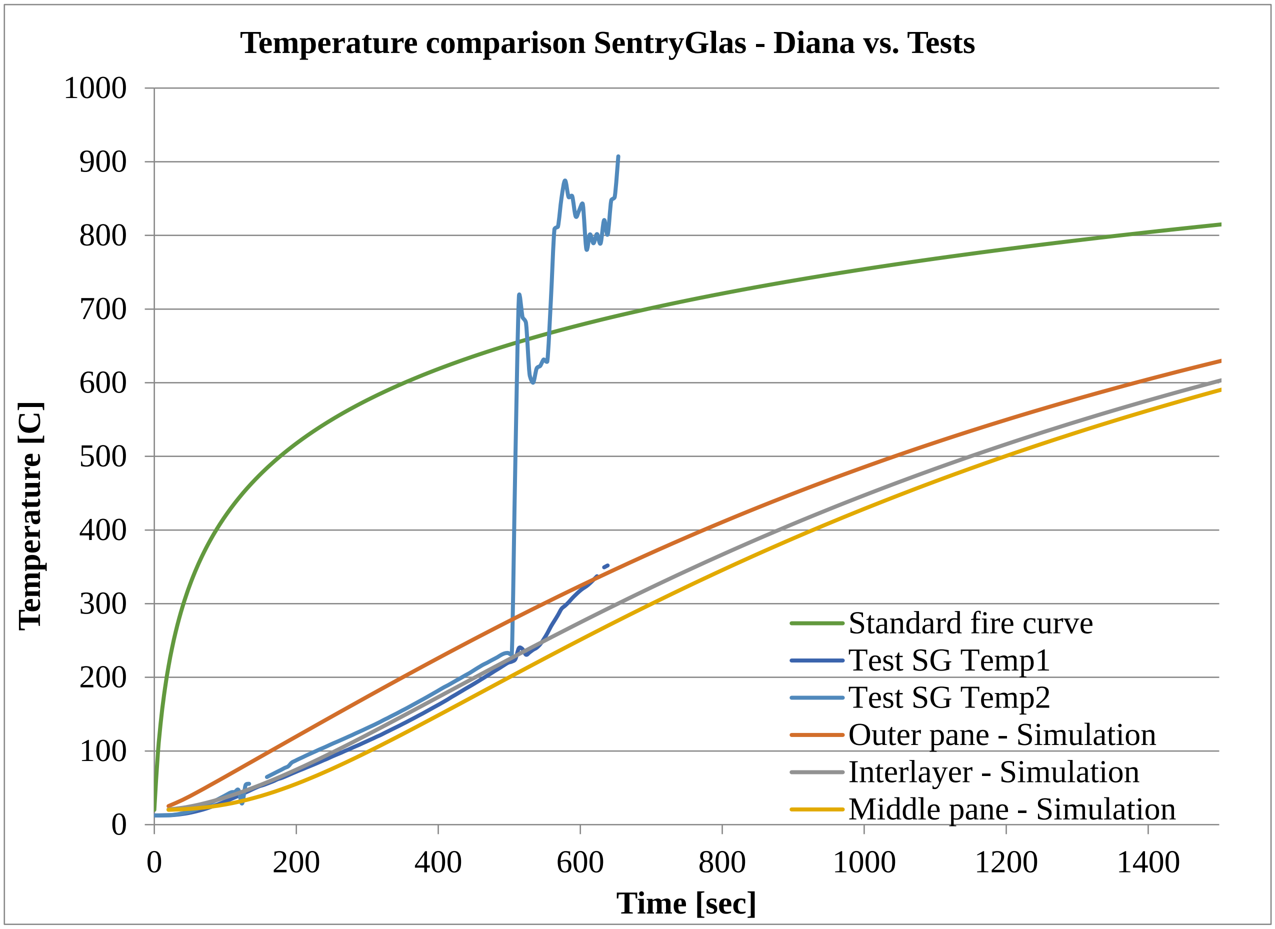


Figure 71 – SentryGlas comparison between thermocouple temperature readings and the simulation values from Diana heat flow analysis.

SentryGlas interlayer beam

The modelled beam is an annealed glass beam laminated with SentryGlas interlayers. In the figure above the simulation results of the heat flow analysis can be seen. The values of the experimental test show that the beam follows the simulated temperature values of the interlayer nicely for at least 500 seconds. Just after this moment the values for the SentryGlas beam are no longer available due to the thermal fracture of the beam in the physical test.

What is interesting to see is that the outer glass pane has a much higher temperature than the inner glass pane and the interlayer. The values of the test and simulation correspond with the interlayer values, which should be the case.

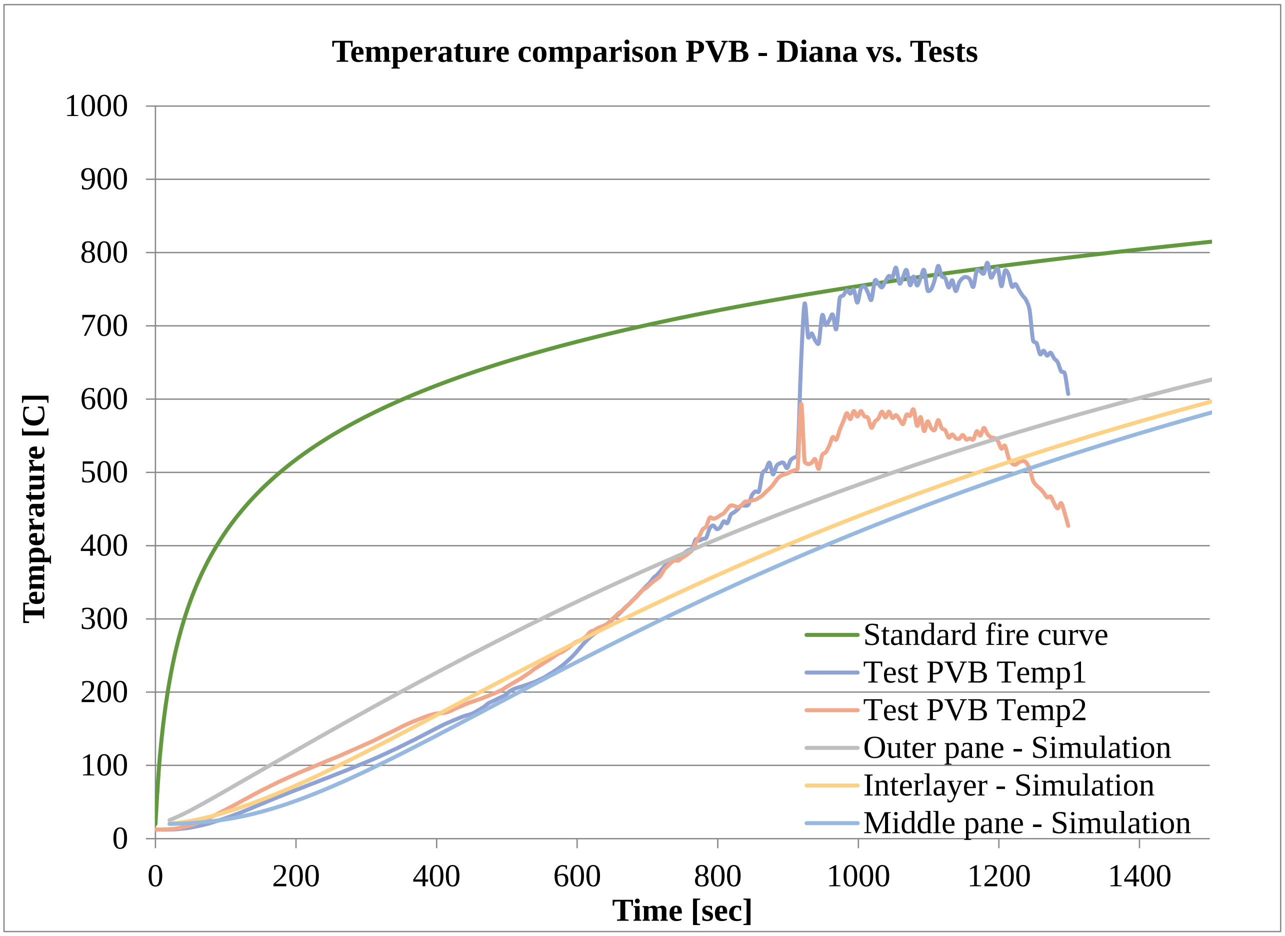


Figure 72 – PVB comparison of the thermocouple temperature readings and the simulation values from Diana heat flow analysis

PVB interlayer beam

The figure above shows the temperature plot of a glass beam with PVB interlayer. The values available for the annealed PVB beam are available for a longer period than the SentryGlas beam. What can be seen from the comparison of the physical test and the simulation is an agreement between the two curves during the first 600 seconds or 10 minutes. The temperature values of the test vary a little above and below the curve of the interlayer. After 10 minutes the temperature readings start to increase rapidly. This is the moment that the PVB interlayer has been burning for some while which eventually softens the interlayer after which the thermocouple becomes exposed and the values measured are no longer just the PVB interlayer but also the oven temperature. At a certain point the temperature value can be seen to match the standard fire curve. During the simulation the interlayer does not soften and drip, exposing the thermocouple. The interlayer only heats further according to the material properties in combination with the fire curve. This explains why the physical test measurement differs from the simulation values. The values of the simulation validate the values obtained from physical testing.

Realisation regarding material properties

While simulating the Diana model the insight hit that the material properties known only allowed to model annealed glass beams. As can be seen above the values correspond with the physical test. However, when wanting to model a heat strengthened or fully tempered glass beam to validate the values found in experimental testing the realisation hit that different thermal properties were not available.

Test 4 – Final Test with application

The fourth and final test performed during this graduation thesis 3 glass beams are tested. To be able to easily compare the results from this test, three identical beams are taken as a basis. The test set-up is loaded with 115 kg as in the first two tests and the EMPA test (C. Louter & Nussbaumer, 2016)

Due to the time constraint of graduation the choice is made to use 3 identical beams that are available from the initial set of beams from the EMPA testing by Louter. From this set 3 heat-strengthened beams with PVB Interlayer are available and are used.

After the analysis of the former tests it seems important to protect the surface of the glass and the bottom edge of the interlayer from direct heating. This test experiments with three methods that could achieve this. The section of the three methods are shown to the right.

Literature from the tests performed by Veer shows the potential of using an intumescent paint FlameGuard HCA-TR, developed to foam and expand at elevated temperatures.(Veer et al., 2001) The expansion forms an insulating carbon char that blocks the direct heating of the surface. The testing by Veer and Bokel was done a one side heated beam loaded with a static load and failure time was above 30 minutes. Other intumescent options would be the intumescent interlayer Pyrostop from Pilkington or VetroFlam from Vertrotech Saint-Gobain. This is an interlayer and not a paint that can be applied.

Eventually the choice is made to apply HCA-TR from FlameGuard, other options would ask to develop a new beam with a different section that would have to be ordered from Pilkington, Saint-Gobain or another manufacturer able to apply a beam with an intumescent interlayer. Unfortunately, the decision of using an intumescent coating or paint in the final test was made at a later stage during the graduation, therefore eliminating the option of ordering specially made beams.

The HCA-TR would not be the eventual coating that would be used on structural glass designs, this has to do with the translucent nature of the coating. Where glass is fully transparent, the coating has a milky white tint. This is however not relevant for the initial testing of an intumescent

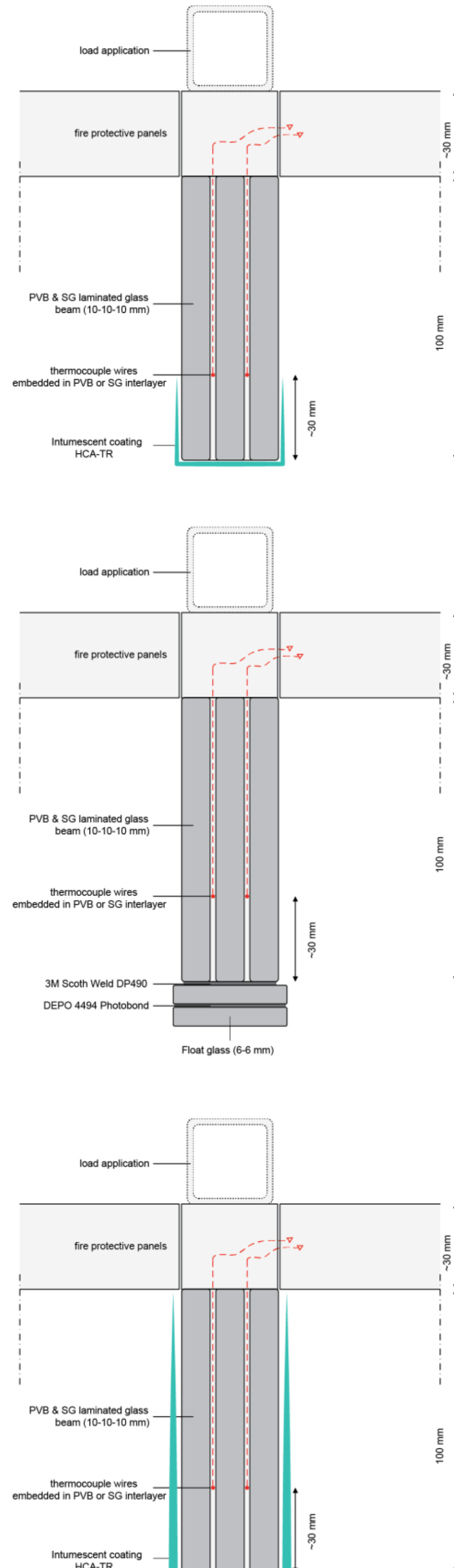


Figure 73 – Schematic section of the 3 modified beams. From top to bottom, Beam 1, 2 and 3

coating applied on structural glass beams under fire loading. During the test the coating will foam at temperatures above 100-150 C which is achieved after a small 15-20 seconds in a standard fire curve. What should be mentioned is that an intumescent interlayer is laminated underneath a sacrificial layer of glass, slowing the heating process before the interlayer expands. In the meantime, the sacrificial layer of glass protects the interlayer from accidental damaging during its lifetime.
Two beams are coated with HCA-TR, with a different surface area. Beam 1 is coated along the bottom 3 centimetres on the side and the full bottom of the beam. The remaining 7 centimetres of the side of the beam are left untouched. The second beam is fully coated on the three sides of the beam that are directly heated during tested, the two sides and the underside of the beam.

A different method that is tested tries to protect and insulate the bottom edge of the PVB and SG interlayers by adding additional glass layers to the underside of the beam. The additional material is allowed to heat up and eventually fail, this material is not added as structural component but merely as thermal stop. Of course, other materials a would have better material properties to form the thermal stop underneath the glass beam, however the transparency of glass is continued when using glass underneath the beam.
This beam from the set of three has two stacked slats of 6mm float glass that are bonded together with DELO 4494 UV Photobond and are attached to the underside of the beam with an epoxy from 3M, DP490. This epoxy is chosen since the underside of the beam is not perfectly flat due to the irregularities in the lamination process.

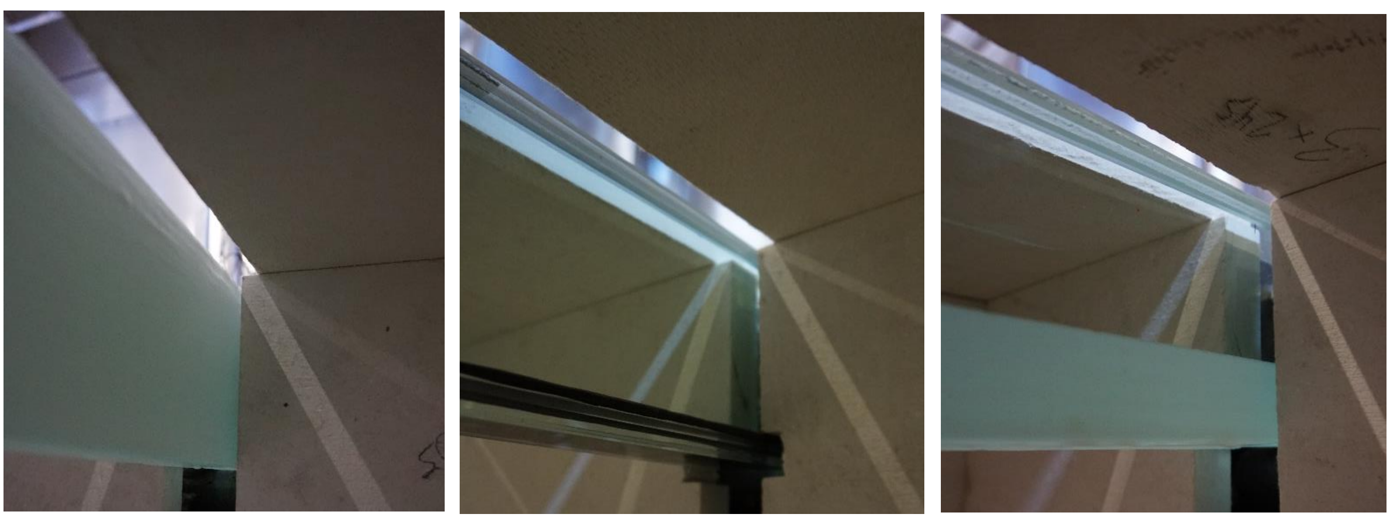


Figure 74 – Images of the modified beams placed in the test set-up – Left, 10 cm three sided HCA-TR intumescent coating – Middle, 6-6 mm glass on underside of the beam – Right, 3 cm HCA-TR intumescent coating

Observations during test 4

Test #4 - 115 kg

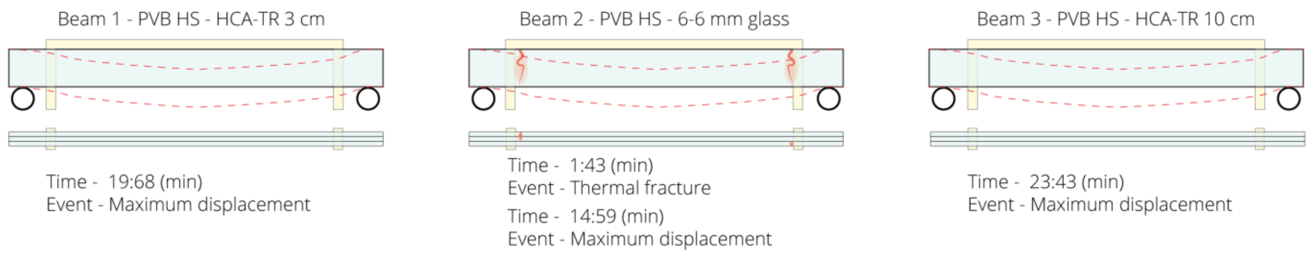


Figure 75 - Graphic representation of test 4 showing the method of failure and corresponding times

During the last and final test performed at Efectis, the oven camera was already in use by a different client. Therefore, the observations are only a summary of the observations done on the outside of the test set-up which are recorded on camera.

Right at the start of the test a large amount of moisture and steam is visible above the Promatect panels, this is probably moisture from either the intumescent paint or the Promatect panels. The intumescent paint is a water-based paint applied with a paint roller after which it is set to dry. Perhaps the coating still contains water that by heating evaporates.
A different possibility might be moisture from the Promatect panels. The panels used in this test are a new set of panels, cut to size, that may contain moisture since it is a gypsum-based panel.

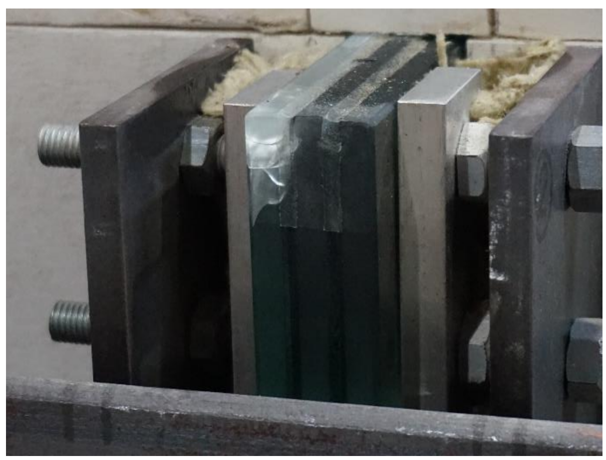


Figure 76 – Thermal fracture in beam 2 during test 4

Directly at the start(1.43min) beam #2 fractures in two panes of glass, since it is heat-strengthened glass the cracks run through the length of the beam and is visible on both sides. Figure ….. on the right shows one of the cracked panes of the beam in the support. On the other side of the beam 2 cracked panes are visible in the camera footage.
Eventually 15 seconds later, 2 minutes into the test, the 3rd pane also shows a crack on the camera footage. The beam however does not fail, it remains able to carry the load resting on top.

After a period in which the beams remain stable, 9 minutes and 7 seconds into the test the steam seems to be a combination of moisture and smoke. Smoke from the interlayer or adhesive applied in beam #2. This is followed by the first flickering of flames is visible through the glass of beam #2 and through reflection via beam #1.

Figure 77 – A still of further fracture in beam 2 visible on video footage

In the meantime, beam #1 & #3 show no flames. Beam #3 doesn't even show the reflection of the flames underneath #2. This is a confirmation that the intumescent paint applied on three sides of the glass beam is functioning as expected, blocking light and protecting the glass from direct heating. What the expanded intumescent coating looks like or how thick the layer has become cannot be seen from the camera footage on the outside of the oven, it is therefore unfortunate that the oven camera was not available. Afterwards, photos are taken of the test set-up that shows residue of the expanded intumescent coating, these can be seen below.

Figure 78 – Intumescent residue of the HCA-TR intumescent coating on the test set-up after test 4

The colour of beam #1 and #2 changes(11.01min) from the blue/green tint to the intense yellow and orange glow of the flames underneath. During the intense flames created by the adhesive and interlayer of beam #2, the beam undergoes some additional cracking. This is visible on the camera footage as one of the outer panes undergoes additional fracture, the glass becomes a bit lighter in colour.

Before the dying out of the flames underneath beam #2 it starts to displace. The displacement becomes visible 14.50 seconds into the test. According to the data the beam fails 10 seconds later due to the exceeded rate of displacement. During the failure and displacement of the beam, the amount of smoke produced increases significantly. Perhaps due to the already cracked beam allowing openings to form from which the interlayer can burn, aside from the exposed underside. This is however an interpretation and cannot be confirmed from the observation.

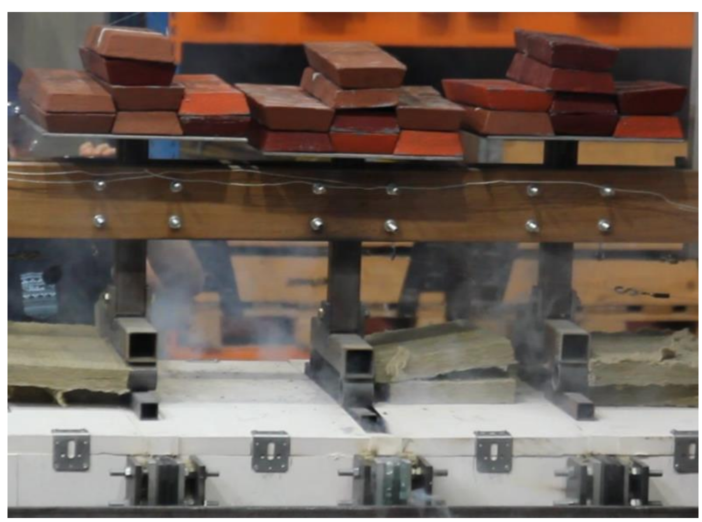


Figure 79 – Displacement of beam 2 reaches approx. 30 millimetres

At a certain point the promatect panel used to cover the set-up deform a little, leaving a small gap from which hot air escaping the oven hits the wooden portal causing the portal to smoulder. This however does not have an effect on the test itself.

Beam #2 has deformed a clear 30mm after 17 minutes and 19 seconds. In figure 80 the height difference is clearly visible between the loads of each beam and that the 4-point bending set-up on the promatect has dropped 30 mm. The deflection rate increases rapidly and the maximum displacement is eventually reached(17.54min). Beam #1 and #3 seem stable and no flames visible.

After 18 minutes a sudden cloud of steam and smoke is produced above beam #3. The cloud of smoke has a yellow tint, that escapes from the opening between the narrow slats of promatect on top of the beam. The smoke continues for a while.

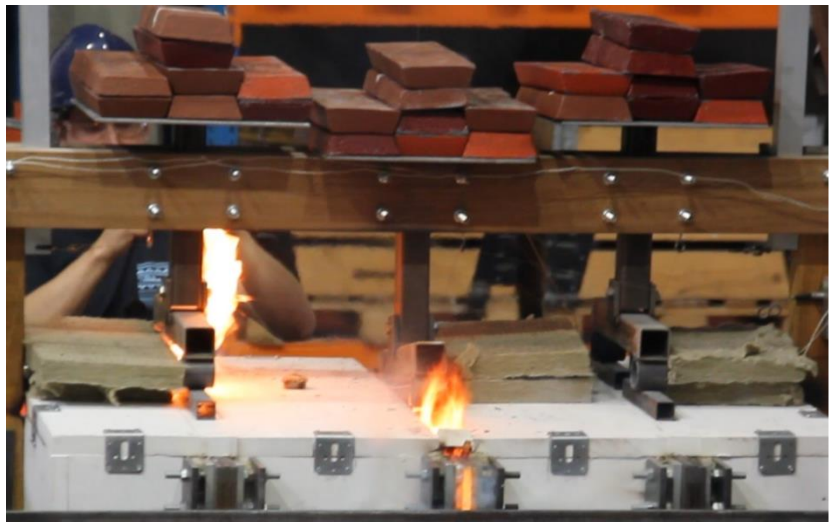


Figure 80 – Ignition of the smoke and fumes escaping above beam 3 with 10 cm of HCA-TR intumescent coating. The interlayer decomposes from the top of the beam.

After the failure of beam #2 flames escape from the opening that remains. These flames or the overall heat of the oven and set-up eventually(19.20min) lead to the ignition of the smoke above beam #3 as can be seen in figure 81. This leads to the assumption that the cloud of smoke is the evaporating PVB interlayer from the laminated glass beam. There are no flames visible through the glass beam, leaving the conclusion that the intumescent layer is still has effect. However somehow the interlayer has heated significantly at the top of the beam and is now evaporating from the top. The beam is coated on three sides; however, the top of the beam was not coated. The top of the beam is covered by fire protective promatect panels, these panels stop fire but do heat up. This leads to the assumption that the top of the beam heats from the top by the small amount of air and the contact and radiation between the promatect panels and the glass or interlayer.

After 20 minutes and 30 seconds, a slight displacement is visible in beam #1. The displacement grows to approximately 15 mm over a period of a minute. At the same time, light of flames becomes visible through the glass of beam #3, possibly a hole has appeared in the expanded intumescent coating. At 22,5 minutes beam #1 has reached the maximum deformation.

The first deformation in beam #3 becomes visible on the footage after approximately 23 minutes. Beam #3 eventually reaches the maximum deformation after 25 minutes and 18 seconds. In the meantime, beam #1 has dropped into the oven. After shutting down the oven, beam #3 also drops into the oven.

Results of test 4

The beams used in the 4th and final test in this graduation research were identical heat strengthened beams laminated with PVB interlayers. The beams were from the same set of beams used in the three earlier tests, as well as the tests performed by Louter at EMPA. As described above the beams have been adjusted to investigate the effect of 3 methods on the fire resistance of structural glass beams.

The behaviour of the three beams during the test differs from the beams in previous test. The observations show reduced light transmittance during the test with the use of the intumescent paint and a residual strength after fracture by applying the additional layer of glass. From the observation and results it is clear that the additions to the beam have some effect on the performance on the beams.

The interlayer in the three beams is a PVB interlayer. In former tests the PVB interlayer was observed to start burning in an early stage of the test, somewhere between 4-7 minutes into the test. The corresponding temperature measured at first ignition range between 93-140 degrees, registered by the embedded thermocouple.

During the latest test the PVB interlayer starts to burn at a much later stage in the test. The earliest flame recorded occurs just over 9,5 minutes into the test in beam 2, the HS PVB with additional glass protecting the underside of the beam. Apparently, the protecting of the glass and interlayer from direct heating can improve the interlayer decomposition rate. Before the first flame in beam #2 the beam had already fractured in all 3 panes just 2 minutes into the test.
For the HS PVB beam with 3 cm HCA-TR it is difficult to determine if the beam produced any flames during the test before failure. The impression is that around 11 minutes the flames visible through the glass are also flames from the beam with3 cm HCA-TR.
The last beam does not show any flames on the underside of the beam; the interlayer of the beam decomposes from the top downward. This results in a cloud of gas that ignites at a certain point.

The measured temperature at the moment that the flames form ranges between 240-280 degrees. This at least 100 degrees higher than in the other tests. A probable explanation could be that the softened and possibly decomposed interlayer has until that point not come in contact with the oven air. Another might be that the interlayer heats evenly without large temperature differences between the underside and at the location of the thermocouple.

Table 15 – Results and observations of test 4

PVB Beams	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	First flame	Start Temp.
PVB Heat strengthened	5	Jelle	Test 4	3 cm HCA-TR	HS PVB - pos 1	115 kg	NO	Delayed heating	241 C	23.91
PVB Heat strengthened	6	Jelle	Test 4	2x 6 mm glas	HS PVB - pos 2	115 kg	(Yes)	Fracture (2min)	280 C	23.81
PVB Heat strengthened	7	Jelle	Test 4	10 cm HCA-TR	HS PVB - pos 3	115 kg	NO	Delayed heating	247 C	23.52

In the table above, table 15 the general observation and test set-up are described. The table below mentions the failure of the beams according to the criteria set by NEN EN 1363-1. The rate of deflection or max increase is set to 0.94 mm/min based on the dimensions of the beam. The maximum deflection is set to 21.16 mm. For each beam the time and corresponding interlayer temperature is listed.

Table 16 – Results of failure time during test 4

PVB Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
PVB Heat strengthened	5	19.68	633.06	22.27	633.06
PVB Heat strengthened	6	14.60	549.30	17.68	720.74
PVB Heat strengthened	7	23.43	582.02	25.27	644.52

This test does not have a set of beams with different thermal treatment. The glass and interlayer of the beams are identical, apart from the varying additions. The question is which addition has the greatest effect on the resistance of a heat strengthened glass beam with PVB interlayer.

The HS PVB beam with additional glass on the underside fractured, however the beam did not fail immediately as the beams in previous tests did. In test 1 the HS PVB beam failed after 14 minutes due to fracture. The beam did not behave with a gradual failure, it broke and dropped into the oven. The beam in this fourth test did undergo fracture, in minute 2 of the test and further fracture in after 11 minutes. The beam was able to withstand the loading of 115 kg up and until 14 minutes in the test. The additional glass on the underside may have ensured some residual strength in the beam in combination with the PVB interlayer. The beam eventually fails after 14,5 minutes as it exceeds the allowed rate of deflection.

The HCA-TR has a substantial effect on the failure time of the beams. While the fractured HS PVB beam in the first test is difficult to compare with, the failure time of the 3 cm HCA-TR already exceeds the failure time of the FT PVB beam in test 2. The failure time of the FT PVB beam was just over 16 minutes. The fully tempered glass is expected to have a higher resistance to heating and fire loading, therefore the effect on the failure time of the 3cm HCA-TR up to 19,5 minutes is interesting. This effect is even larger for the 10 cm HCA-TR which is able to withstand until 23.5 minutes, before the rate of deflection classifies it failed.

The ignition of the gasses and fumes above beam 1 with 10 cm HCA-TR created the realisation that the top of the beam had not been protected with the intumescent paint. The topside of the beam was in direct contact with the fire protective panels. During the heating of the oven the fire protective panels protect elements on the outside of the oven from direct heating, although the panels do heat up from the oven heating. The glass is therefore in direct contact with the heated promatect panels, which in turn heat the glass and interlayer from the top downwards. Furthermore, the glass-promatect connect will probably not be perfect which leaves the top of the beam slightly exposed to heating. The expanded intumescent paint may fill a portion of the gap but probably not all.

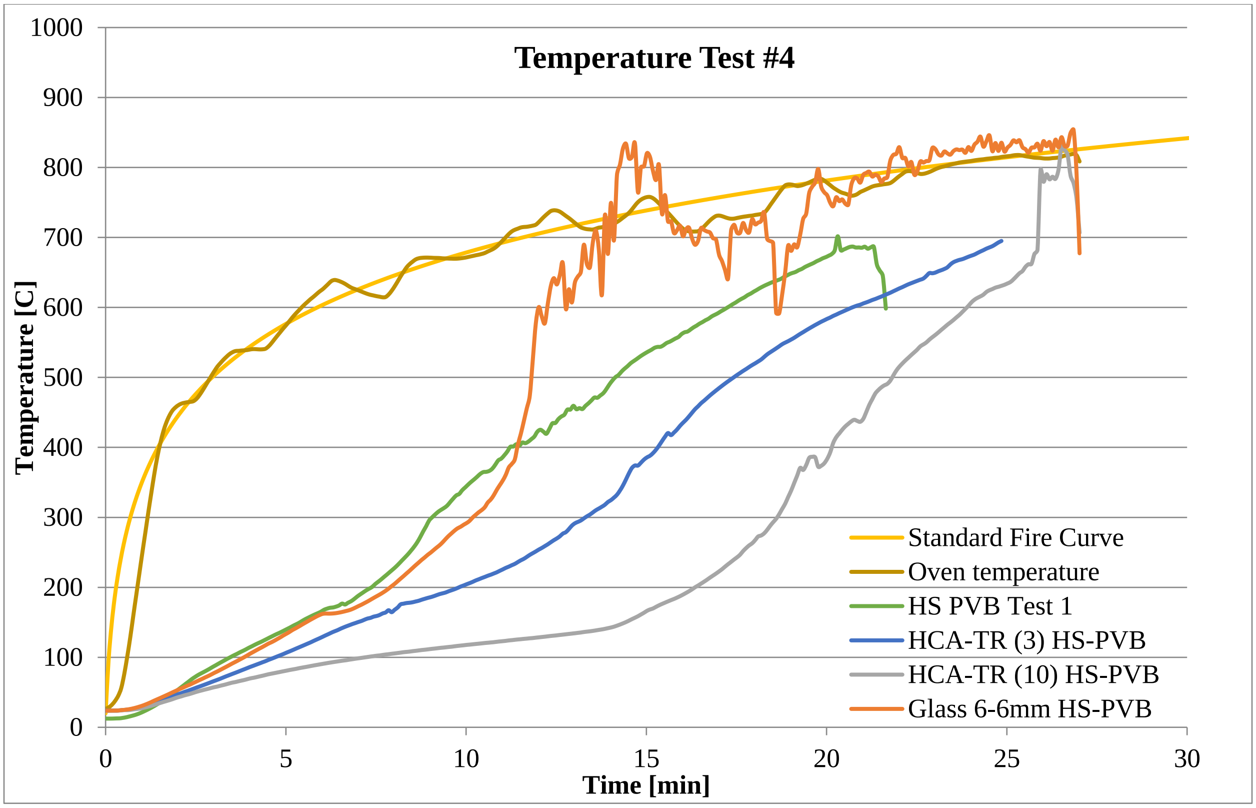


Figure 81 – Thermocouple temperature readings of test 4 – Heat strengthened PVB beams with HCA-TR(10cm), 6-6mm glass addition, HCA-TR(3cm) – A heat strengthened beam from beam 1 is added as a reference

Temperature-Time curve

The plot of the fourth and final test looks different than the plots of previous tests. The temperature readings of the 3 formerly identical beams show large differences with the additions. To show the effect on the temperature curve a reference temperature curve of from test 1 is added to the plot. Furthermore, the measured oven temperature is shown to show the match with the standard fire curve.

The residual strength of the beam HS PVB with additional glass on the underside has influence on its interesting temperature curve. While the beam fails at 14 minutes the temperature readings are well above failure temp, which indicates that the glass delaminated or the PVB had burned up exposing the thermocouple to high temperatures from the oven. Before this moment the temperature increase looks similar to former tests. The beam is able to resist the load resting on the beam for another 3-4 minutes before failing. This is no longer visible on the temperature curve measured for the beam.

The HCA-TR beams show a clear delay in heating compared to the reference HS PVB beam. The 3 cm HCA-TR beam reaches a temperature of approximately 250 degrees after 13 minutes, while the temperature of the oven is above 700 degrees Celsius. The 10 cm HCA-TR shows an even larger delay, the beam only reaches 150 degrees just before 15 minutes into the test. While the temperature in the oven is about 650 degrees higher. At this stage a number of beams in previous tests had already failed.

Just after these two moments in the test the temperature of the two beams with intumescent coating starts to heat quicker. Possibly this is due to the interlayer having decomposed and heated from above. The 3 cm HCA-TR has an unexposed area of glass that heats directly from the oven. The top of the beam

is heated similarly as the 10 cm HCA-TR from the top of the beam, through small gaps and in contact with the heated promatect panels.
It is almost unfortunate that the top of the beam was left unprotected and that the interlayer started to decompose from the top. Even though, the clear effect of the applied protection shows potential for future tests into fire resistant glass using intumescent coatings.

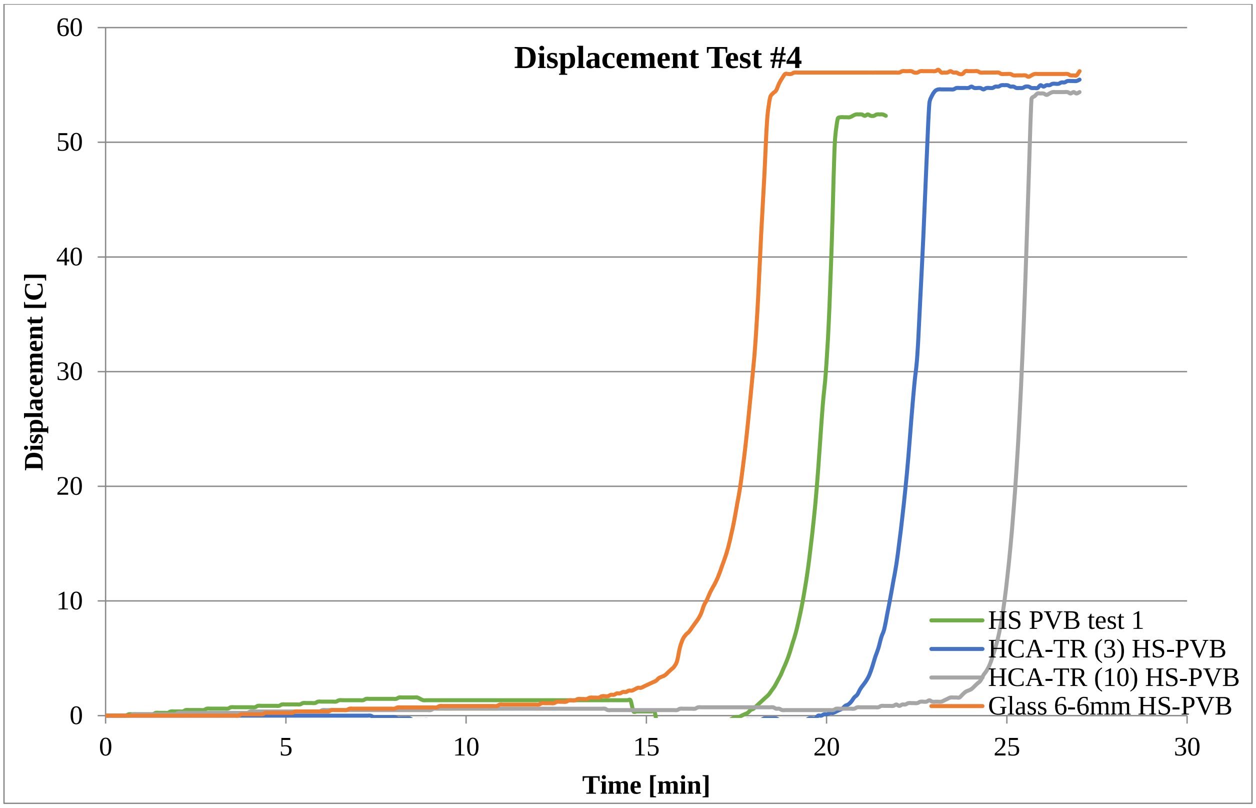


Figure 82 – Displacement readings during test 4 - Heat strengthened PVB beams with HCA-TR(10cm), 6-6mm glass addition, HCA-TR(3cm) – A heat strengthened beam from test 1 is added as a reference

Displacement curve

The displacement curve of the three beams seem similar to displacement of beams that fail from the heating and softening of the glass.

The full fracture of the middle HS PVB beam with 6-6 mm additional glass does not show immediate and full failure. The displacement does occur before the PVB has burned up fully. In most tests this is the other way around, the flames have slowly died down before the beam fails. In the displacement curve a slight irregular movement can be seen just after 15 minutes. The slight bump looks like a slight drop of the beams, this was not observed on the footage. Perhaps one of the moving elements of the set-up was restricted for a moment due to some form of friction.

The two beams that show delayed heating in the temperature curve and the HCA-TR intumescent paint show a delayed displacement in comparison to the reference HS PVB beam from test 1. The failure behaviour is similar to the reference beam and other beams.

Discussion of test 4

The fourth and final test in this research had the aim to develop and test possible modifications to improve the failure time gathered in the first tests. The test set-up would remain the same and the loading was 115 kg. The beams chosen in for this test were 3 identical heat strengthened beams with PVB interlayers. The beams were modified using knowledge from literature and the gathered results from the first three tests.

The modification of the beams was done by hand in the glass labs of the civil engineering department. This was not the initial plan, which was to attempt to order factory grade glass beams with desired specifications from a glass manufacturer. During the graduation time is a limiting factor, the process of contacting a manufacturer had already taken up a lot of time that the decision was made to switch to an alternative approach and prepare the beams by hand.

With the help and sponsoring of FlameXpert the HCA-TR intumescent paint manufactured by FlameGuard was acquired. The intumescent paint was applied with a paint roller and given time to dry. This drying process was important to ensure a fully functioning coating. During the test steam was visible above the test set-up during the start of the heating process. There is a possibility that the intumescent paint did not dry completely. If the HCA-TR is applied in future tests, the drying process should be examined and completed before testing to prevent a lower performance.
The process of applying the HCA-TR as a simple rolled on paint is not the eventual method that would be applied in a building element. The intumescent paint is left exposed to possible damage during placement and use, which could affect the performance of the coating. Furthermore, the HCA-TR is a water-based solution that could slowly dissolve due to moisture in the air, this would lower the performance over time, in turn asking for continuous service to maintain the desired performance.

The beams tested did not achieve the minimal fire resistance of 30 minutes as set by building regulations. This was the initial goal of this graduation research after analysis of the results from the EMPA tests. The fact that the goal has not been reached does not mean that glass beams cannot achieve a fire resistance of 30 minutes or higher. The experience and knowledge that has been developed through the research is of importance for further development. The improvements in failure time that have been done by applying an intumescent paint by hand show the possible potential of intumescent coatings of interlayers.

Conclusions

The final test in the four tests performed at Efectis supplies results for the fire resistance of structural glass beams with additional measure to improve failure time. The behaviour of the modified HS PVB beams has been compared against data from literature research and the outcome of the previous three tests. The results offer a number of conclusions to improve the overall fire resistance of glass beams. These conclusions are summed up in the following section.

- The failure times of all three beams with additions to improve the resistance of the beam, do not meet the minimal requirement of 30 minutes as set by building regulations. The closest time is 23,5 minutes.
- The protection of the top 3 centimetres of the beam as performed by Louter at EMPA has a better effect on the fire resistance of a laminated glass beam than the modified beams in this test.

- The HS PVB beam with additional glass eventually performs less than the HS PVB beam in test 1
- Adding additional material, in this case glass, on the underside of the beam has a positive effect. Mainly in the form of residual strength after fracture of the glass at high temperatures. Especially in the first test, the interlayer of the two fractured beams is unable to maintain the composed laminate.
- Furthermore, the additional glass seems to postpone first flames of the interlayer by protecting it from direct heating.
- Residual strength of fire-resistant glass beams may add an additional fail safe in case of thermal fracture.

- The application of a protective layer on the surface of the glass beam has an improved effect on the performance of the glass beam. The full protection of three sides of the beam offers a greater protection than protecting only the underside of the beam.
- The 3-centimetre HCA-TR improved failure time by 2,5 minutes
- The 10-centimetre HCA-TR improved failure time by 6,2 minutes
- The HCA-TR intumescent paint had a clear effect of delayed heating during the fire test. The findings of Veer(Veer et al., 2001) correspond to the findings in this final test.
- The fact that the temperature of the 10 cm HCA-TR beam was only 150 Celsius after 15 minutes indicates that the heat of the oven had a very small effect on the beam until that moment.
- Not protecting the top of the beam may probably have influenced the failure time of the HCA-TR beams, causing the beam to heat from the top.

- The HCA-TR does not create a fully transparent beam, which is part of the initial goal of this graduation research. The intumescent paint gives the glass surface a milky and translucent look. The preferred method would be to use an intumescent interlayer in future tests. These intumescent interlayers can be applied with full transparency.

Discussion

The fire furnace tests have given additional insight on the fire resistance of structural glass beams. While the tests were the first attempt at performing large scale fire tests, the outcome has provided insights that can benefit the future development of structural glass beams. As with every experimental research there is a possibility that decisions made beforehand can affect the eventual outcome and lead to results that raise questions. This experimental research is no different.

The varying behaviour of the beams in test 1 and 2 resulted in less clear results than the results at the EMPA tests. The behaviour of the beams and the corresponding failure times have to be analysed while taking the external influences into account. This makes it more difficult to draw clear and specific conclusions.

The choice of combining the beams with the lowest resistance and the beams with the highest resistance in the first two tests may could have been re-considered in hindsight. The different behaviour of the PVB and SentryGlas interlayer has clearly had effect on the behaviour of the beams during the tests. Ideally the beams are tested individually or multiple times to eliminate chance and external influences. This was not possible due to the limited fire furnace tests.

The modifications to the beams in the 4th and last test were done by hand in the glass labs of the civil engineering department. This was not the initial plan, which was to attempt to order factory grade glass beams with desired specifications from a glass manufacturer. During the graduation period, time turned out to be a limiting factor, the process of contacting a manufacturer had already taken up a lot of time that the decision was made to switch to an alternative approach and prepare the beams by hand.

The beams tested during the 4 tests did not achieve the minimal fire resistance of 30 minutes as set by building regulations. This was the initial goal of this graduation research and was based on the Dutch building regulations. The fact that the goal has not been reached does not mean that glass beams cannot achieve a fire resistance of 30 minutes or higher. The experience and knowledge that has been developed through the research is of importance for further development. The improvements in failure time that have been done by applying an intumescent paint by hand show the possible potential of intumescent coatings of interlayers.

Comparison of results EMPA & Efectis tests

In the beginning of the graduation research the decision was made to continue the research started by Louter at EMPA in Switzerland(C. Louter & Nussbaumer, 2016). The goal of both researchers was to create a better understanding of the behaviour of structural glass beams under fire loading. The research done by Louter provided interesting data, providing a hopeful basis for the further development of fire-resistant glass beams. Although the data might have been favoured by the test set-up used.

To figure out wat the effect of the configuration could have been on the resistance of the glass beams, the test set-up in this research would be based on the set-up used at EMPA. The possibly favourable configuration of the beams would be adjusted to a eliminate one of the favourable aspects.

Table 17 – Failure comparison of the PVB beams between the EMPA test and the Efectis test

PVB Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	34.6 min	14.9 min	19.8 min
Heat Strengthened	39.6 min	17.2 min	22.4 min
Fully Tempered	42.8 min	16.2 min	26.6 min

Table 18 – Failure comparison of the SentryGlas beams between the EMPA test and the Efectis test

SentryGlas Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	32.9 min	7.8 min (fracture)	25.1 min
Heat Strengthened	41.8 min	17.0 min	24.8 min
Fully Tempered	48.0 min	17.5 min	30.5 min

The tables above show the difference between the failure times of 6 types of glass laminated beams in each test. The difference between the tests is at least 20 minutes up to a full 30 minutes, which is the eventual aim for a fire-resistant glass beam.
When we take a look at the failure times within each test, the difference in failure time is larger in the EMPA test. The time difference between annealed, heat strengthened and fully tempered beams are respectively 5 and 3 minutes for PVB interlayers, the difference in the SentryGlas is 9 and 6 minutes. The difference is less clear in the Efectis tests where the largest difference is 2 minutes between the annealed and heat strengthened beam with PVB interlayer.

The EMPA test results show a clear fire resistance in order of thermal treatment. This is less clear in the results developed in this graduation research. One of the obvious explanations is the different beam set-up by placing the fire protective panels above the beam. The protected top $\frac{1}{3}^{rd}$ or 3 centimetres of the beam in the EMPA test seem to have had a strong beneficial effect on the overall performance.

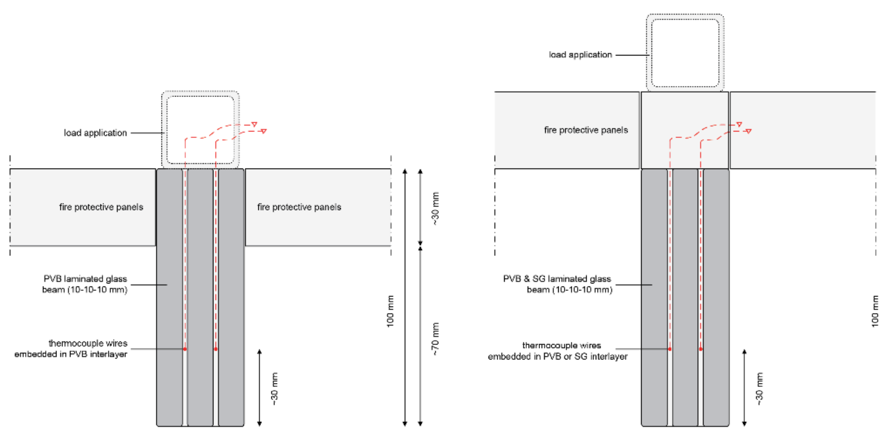


Figure 83 – Schematic section showing the difference in beam set-up between the EMPA and Efectis tests

During the heating of the beams at EMPA the top 3 centimetres is blocked from direct heating. The protected area is heated via indirect heating through the material, while during this research the beams are fully loaded by direct heating on 3 sides including the top $\frac{1}{3}^{rd}$.

The tempering or thermal treatement creates internal pre-stress in the glass. The distribution through thickness sees a compressive pre-stress on the surface of the glass and a tensile pre-stress in the centre. The glass laminated beams are laminated with the edges beside each other. In the EMPA test, as can be seen in figure 85 the protected top 3 centimeters of the beams shield a portion of the initial pre-stress. The large difference in failure time in EMPA test and the comparisson to the results in this graduation research may be related to the protection of this area of initial pre-stress.

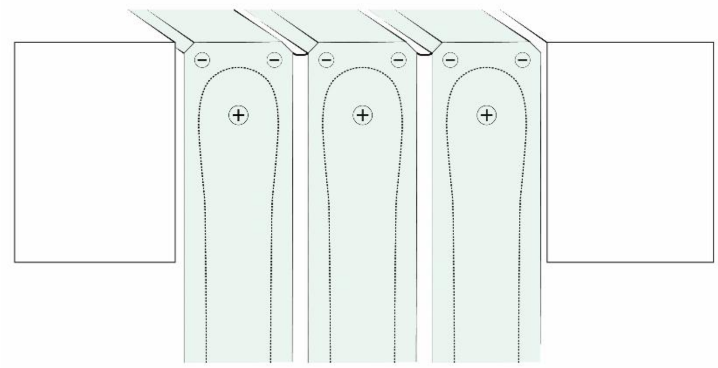


Figure 84 – Schematic representation of the internal pre-stress in the top of the tempered glass beams.

This reasoning leads to the question if the tempering of glass can be linked to the failure time of structural glass beams. Additionaly the question is what effect tempering has on the material properties of glass, apart from inducing internal pre-stress.

The effect of tempering on the material properties of structural glass

The fact that thermal treatment leads to pre-stress has been discussed in the beginning of this thesis. A compressive stress in along the outer surface and a tensile pre-stress in the centre of the glass. This is an internal stress equilibrium that sets in after heating the beam to 650 Celsius after which the surface cooling results in internal stresses. Nielsen 2010(Nielsen et al., 2010) describes the typical development of internal stresses during the cooling process.

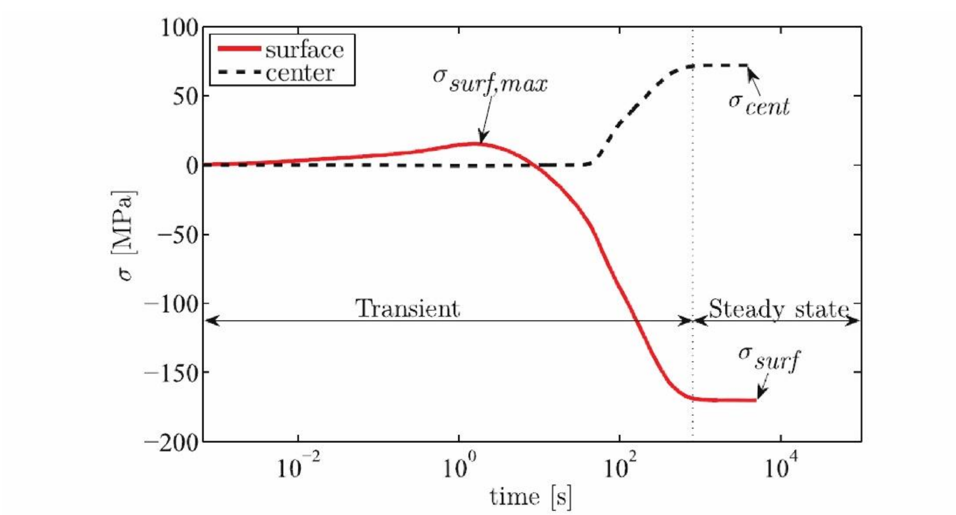


Figure 85 – Typical development of the surface and centre stresses during the cooling process
Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

At the initial moment that the cooling process starts the glass surface shrinks due to the thermal expansion properties. The shrinking of the glass creates a slight tensile stress before the centre of the glass starts to cool. Eventually during the cooling process, the internal stresses reach an equilibrium and the glass sets in a steady state.

The rate at which glass cools not only has effect on the internal stress distribution. In his research Nielsen describes the element arrangement at different cooling rates. While the amorphous structure of Soda lime silica glass has a low crystallization rate, the glass atoms could theoretically set in a perfect crystalline structure, the chance that this occurs in soda lime glass is fairly small. The cooling rate influences the setting of the atoms and thereby determining the volume of the glass as it cools down. This phenomenon is known as the volume relaxation due to mass conservation. A higher cooling rate leads to glass with a slightly larger volume than glass cooled in a lower cooling rate. Figure …. shows the volume difference between a crystalline structure, regular cooled glass and fast cooled glass.

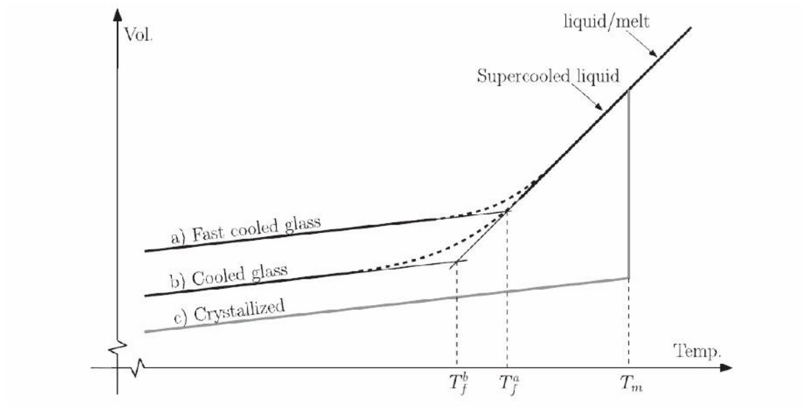


Figure 86 – Variation in volume at different cooling rates. (a) Fast cooled glass (b) Cooled glass (c) Crystallized state that shows an abrupt change in volume when above melting point T_m
Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

This phenomenon has been described mathematically by Narayanaswamy(Narayanaswamy, 1977). His research looked into the effect of several cooling rates on the internal stresses and the correlation to the density. He states that tempered glass has a slight density distribution through the thickness of the material. The faster cooled surface has a relatively lower density than the centre. The density variations

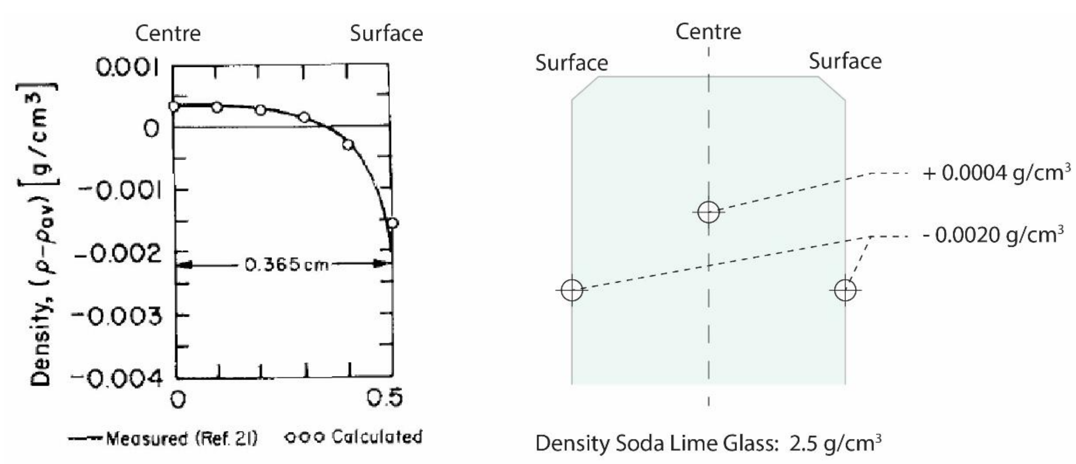


Figure 87 – Left shows a figure of calculation and measurement of the through half-thickness density variation in after cooling of tempered glass. Right shows the effect on full thickness
Source: Stress and structural relaxation in tempering glass - Narayanaswamy

that he describes are small but present nonetheless. The density differences in his example are in order of 0.0025 g/cm^3 or 2.5 kg/m^3 between the centre and surface of the glass. The figure from his research paper set out against the full width of glass can be seen in the following figure. He mentions that approximately 24% of the present internal stresses are the result of the density variation.

The problem with these findings is that it does not explain why tempered glass heats up slower than typical annealed glass in the fire furnace. The expectation might be that a lower density in the outer surface would result in a higher heating rate. However from the experimental testing, the opposite effect is witnessed.

Looking back on the results from experimental testing done by Louter as well as tests performed during this graduation research indicate that the tempering and thermal treatement has influence on the overal fire resistance of structural glass beams. The reasoning currently is that the tempered glass absorbs energy during the heating process. What the reason for this absorbtion is and what influence this has on the glass is currently unknown to the author. The most reasonable explanation currently is that a reversed process of the internal stress formation takes place, that the reversed process of pre-stress absorbs energy changing the thermal properties of the tempered glass.
However, this reasoning in turn raises a large amount of additional questions of which the answer needs further research.

Lastly, the limited number of tests strongly influences the possibility to define strong conclusions based on the test data. If a large number of tests would have been performed the trend throughout the tests would be clearer than some of the outcomes currently are. Statistically the larger number would eliminate the effect of chance. Currently some of the conclusions have been made according to reasonable expectation.

Conclusions

During this graduation research four test have been performed to investigate the fire resistance of laminated structural glass beams. The main conclusions that can be drawn from literature research is that additional experimental research should be performed to investigate the fire resistance of structural glass. This graduation thesis aims to add knowledge and results to the common knowledge regarding the fire resistance of structural glass. The tests at Efectis have been done in such a way that the results can be of some value to future studies and can be compared to research done in former studies. This is of importance to develop structural glass building elements that may be applied in buildings that require certified elements with a specific fire resistance.
The tests on the various laminated structural glass beams has developed the following conclusions.

- The structural glass beams tested during this graduation research did not meet the minimal fire resistance goal of 30 minutes, however a step in the right direction has been made by improving the failure time of a HS PVB beam from 15 minutes to 23,5 minutes.
- Glass beams have the potential to withstand fire loading for at least 30 minutes. Important factors to achieve this are the beam set-up in combination with transparent intumescent or other protective layers.

- The results from the EMPA test performed by Louter(C. Louter & Nussbaumer, 2016) have better failure times. The time difference is at least 20 minutes.
- The protection of the top 3 centimetres of the beam from direct heating seems to have a strong influence on the failure behaviour of the structural glass beams.

- The failure of the glass laminate beams seems to be in the order of thermal treatment. However, the results from the tests performed in this graduation research are not as clear as the results from the EMPA tests.
- Thermal shock during the fire tests results in direct and full failure of the beam.
- The low thermal resistance coefficient of annealed glass resulted in thermal shock of three beams, two with a SentryGlas interlayer and one PVB interlayer.
- Annealed glass does not seem suitable to apply in fire resistant glass beams. There is a realistic chance of thermal fracture and the failure times are lower than thermally treated glass.

- The PVB interlayer started to decompose at lower temperatures than the SentryGlas interlayer. This corresponds to the findings of Debuyser(Debuyser et al., 2017) and the specifications offered by manufactures(Dupont; Saflex, 2018).

- Increased load (115kg-250kg) does not show noticeable effect on the failure behaviour of the glass laminated beams.

- HCA-TR intumescent paint improved the fire resistance of a HS PVB beam. The time improved from 15 minutes to 23.5 minutes.
- Using HCA-TR on 3 sides of the beam, the interlayer temperature had only reached 150 Celsius after 15 minutes, at which point the HS PVB reference beam from test 1 had started to fail.

- The protection of 3 sides of the glass beam with an intumescent coating or interlayer has great effect on the rate of heating of the glass and the laminate interlayers. This has effect on the improved failure time.

- The protection of the underside of the beam with additional material, offered residual strength after fracture. The beam did not fail directly as in the earlier tests.

- Glass beams are strongly affected by the radiant heat produced by flames. The use of a low-e coating on the beams to limit the effect of radiant heating may be interesting.

As mentioned in the conclusions, the failure of structural glass seems to occur in the order of thermal treatment. This is the case for the EMPA test by Louter and can be concluded from this research study. It must be said that the results in this study are not as clear as the results that the EMPA test.
The reason why this order of failure takes place cannot not be answered in this graduation research. Unfortunately, the literature studied and the measurements taken cannot explain the difference in heating rate between tempered and non-tempered glass beams. Further research is needed on the different thermal properties of tempered glass to describe why these two studies find these results.

Design Recommendations

An aim of this research paper is to propose a design method for fire resistant glass beams. Using the findings from the experimental testing and literature studied a number of design recommendations are developed which can be used for structural glass beams.

- Use fully tempered glass - From the failure behaviour of the various types of glass, the thermal treatment of the glass has effect on the performance under fire loading of the beams. Annealed glass has a low thermal resistance and the three tested annealed beams have failed due to thermal fracture. From the thermally treated beams the fully tempered glass has the highest fire resistance according to results. The time to failure is higher for fully tempered glass than heat strengthened glass due to a slower heating rate of the beam.

- Use SentryGlas interlayers – The findings in literature and the experimental study show that the decomposition temperature of SentryGlas is higher than the PVB interlayer. Furthermore, during the tests of this graduation research the PVB interlayer started to burn a lot sooner than the SG interlayer. The different behaviour of the two interlayers is described as well by Debuyser and Louter as well as the material properties of the interlayers by DuPont.

- Implement a transparent intumescent interlayer on 3 sides - The effect of using an intumescent interlayer is not a new idea. However, since fire resistant glass beams have not yet been developed, using an intumescent interlayer in the design for fire resistant structural glass beams can be useful to achieve the requirements set by building regulations. The transluscent HCA-TR intumescent paint used in the 4th experimental test is applied on the outer surface of the glass, leaving it prone to damages and creating a milky translucent appearance of the glass beam. Intumescent interlayers such as Vetroflam of Vetrotech or Pyrostop from Pilkington are fully transparent interlayers that could be interesting in further design studies.

- Protect the top tempered 1/3rd of the beam – The large difference in the failure time between the EMPA test and the Efectis tests shows the potential of protecting the top third portion of the glass beam. The protection of this area protects it from direct heating of the glass, which ensures a slower heating rate and an eventual later failure. The exact method how to achieve this is up to the specific design of the beam and the building application.

These recommendations offer a first step to design fire resistant glass beams. Not all recommendations have been tested and confirmed. The recommendations have been made according to research findings throughout this graduation research and should be seen as a 'living' set of recommendations. New research findings should be incorporated to develop certified fire-resistant structural glass beams in the near future.

Research Recommendations

Structural glass beams are not able to be certified at the moment with the available knowledge. Additional experimental testing and literature research must be performed to create a more complete understanding of the behaviour of structural glass beams during fire loading. A number of possible research topics are proposed in these recommendations.

The biggest question related to the fire resistance of structural glass is whether the thermal treatment of glass induces varying thermal properties in the glass. This research could be done on a small scale.

The fire furnace tests of EMPA and Efectis should be repeated using tempered glass from a different manufacturer. The glass from a different manufacturer might slightly differ from the SwissLamex glass.

The effect of radiant heating has been researched by Debuyser, Ahmad and Dahl(Ahmad & Javed, 2018; Dahl & Engineering, 2018; Debuyser et al., 2017). These studies however focus on window glass and the fallout of glass panes. Repeating this research using various thermally toughened glass panes could give an insight if there is different behaviour between annealed, heat strengthened, fully tempered and chemically toughened glass.

Additionally, the radiant heat research could look into the effect of applying a low-e coating on the surface of the glass beam to shield the glass from a portion of the radiant heating that could occur with building fires.

The conclusions in this research paper demand for an increase in the number of tests. The conclusions could be influenced by external factors and chance. By increasing the number of tests, the factor of chance and the external influences could be eliminated from the results.

Lastly, before fire resistant beams can be developed the process must progress by testing different beam configurations, various forms of detailing, larger loads and the effect of time on the fire resistance of structural glass elements.

Application of fire-resistant structural glass

The design of subterranean spaces asks for a lot of attention on the overall experience of these spaces. One of the main aspects that has to be figured out is safety.

Safety is not only a term that can be calculated or measured according to building regulations. While fire safety and resistance are important factors in this graduation thesis, structural glass offers an additional form of safety that other, non-transparent materials, lack. Due to the transparency of glass, light and more importantly daylight can enter the building.

Daylight intrusion is an important factor for the safety perception of underground spaces. The effect is that users perceive the space less as underground space and their orientation inside the building or space improves. (Vakar, 2014)

As a design case, with the aim to show the possible application of fire-resistant glass, an attempt will be made to increase the perception and functional aesthetics of the underground train station in Delft.

This relatively new building has attempted to realise the daylight intrusion into the underground spaces using glass elements. The daylight is captured using structural glass floor panels. These floor panels are supported by a roster of steel flanges that can be seen in the top of figure 90. The side view however does not show daylight, commuters look against the side of dark, high steel construction elements, which in turn creates a somewhat darker atmosphere.

As a design case the structure of glass floor panels and steel flanges will be re-designed using fire resistant structural glass beams according to the proposed design recommendations. The goal is to replace the dark steel beams with transparent glass beams that enhance the daylight transmittance even further.

Figure 88- View of the train platform of Delft
Source: Benthem en Crouwel

Figure 89 – View of the city bus square in front of the station. The glass panels floor panels allow daylight to transmit into the floors below
Source: Frans van Rijnswou

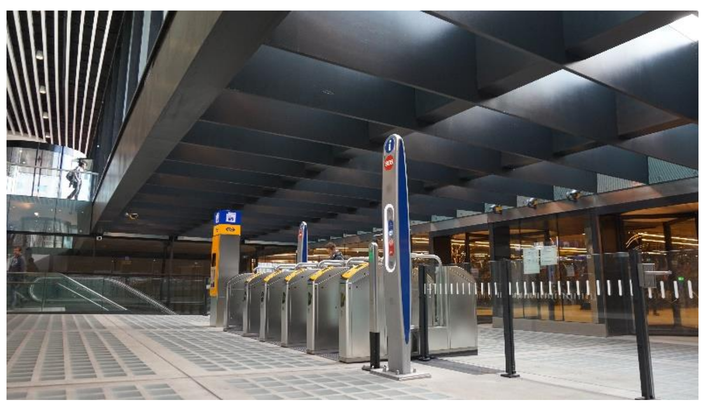


Figure 90 – When standing in the station, the glass floor panels are not visible and the dark steel flanges create a somewhat darker atmosphere Source: Author

Current Situation

Figure 91 - View of the bus square from inside the station, showing the large spanning I-beam just beneath the facade windows

The bus square above ground has an area with glass floor panels. The panels are approximately 800 centimetres wide and 2 metres long laid out in a grid of 3 x 23 structural glass floor panels. These panels rest on top of a network of steel flanges that span the length of the glass panels. The spanning steel flanges are supported by two steel I-beams, covered by wooden panels. Each glass pane is supported on 4 sides by an aluminium frame which rests on top of the steel beams.

Figure 92 - The dark steel beams underneath the glass floor panels

Proposed design

Using glass as the structural material for the floor system is the main interest in this design. In the design of the structural glass floor the findings of this graduation research are applied. The structural glass elements and the combination of glass floor panels and glass beams should incorporate the proposed design recommendations for structural glass beams.

The design recommendations are the following:

- Use fully tempered glass
- Use SentryGlas interlayers
- Implement an intumescent interlayer on three sides of the glass beam
- Protect the top 1/3rd of the beam from direct heating from the underside

The floor will use the same grid of glass panels with a width of 800 mm on the surface of the bus square as the current system. The large steel I-beams that span the total width underneath the glass panels will be used due to the large span. In the images below a set of schematic representations show the design configuration between glass beams and floor panels.

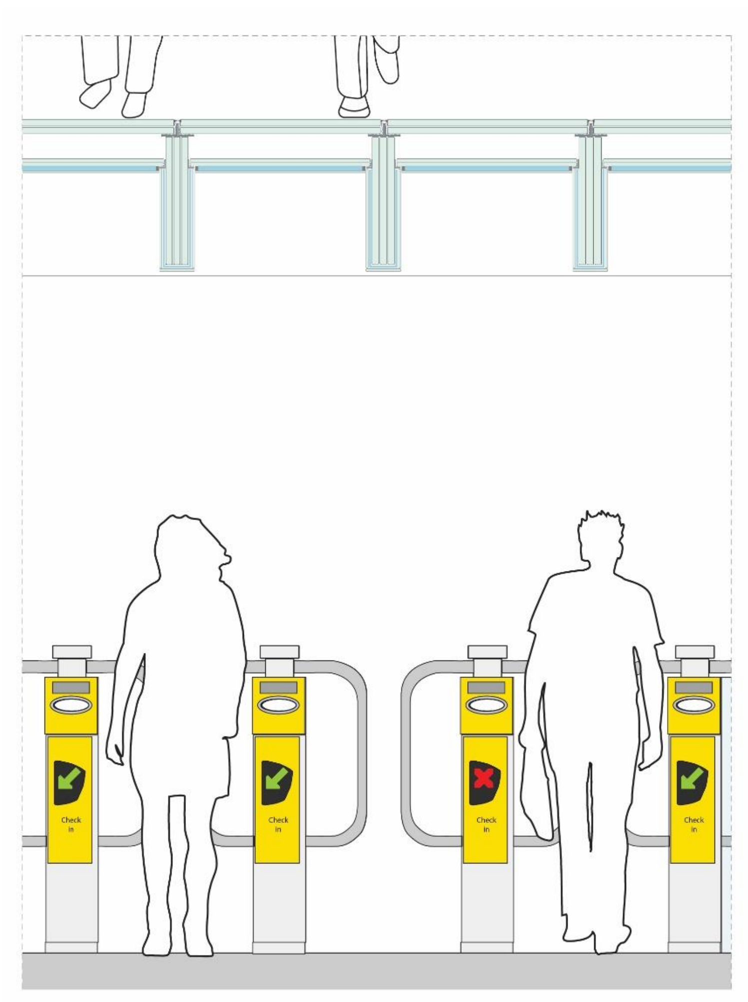


Figure 94 – Cross section showing the proposed glass beams above the check-in gates of the NS

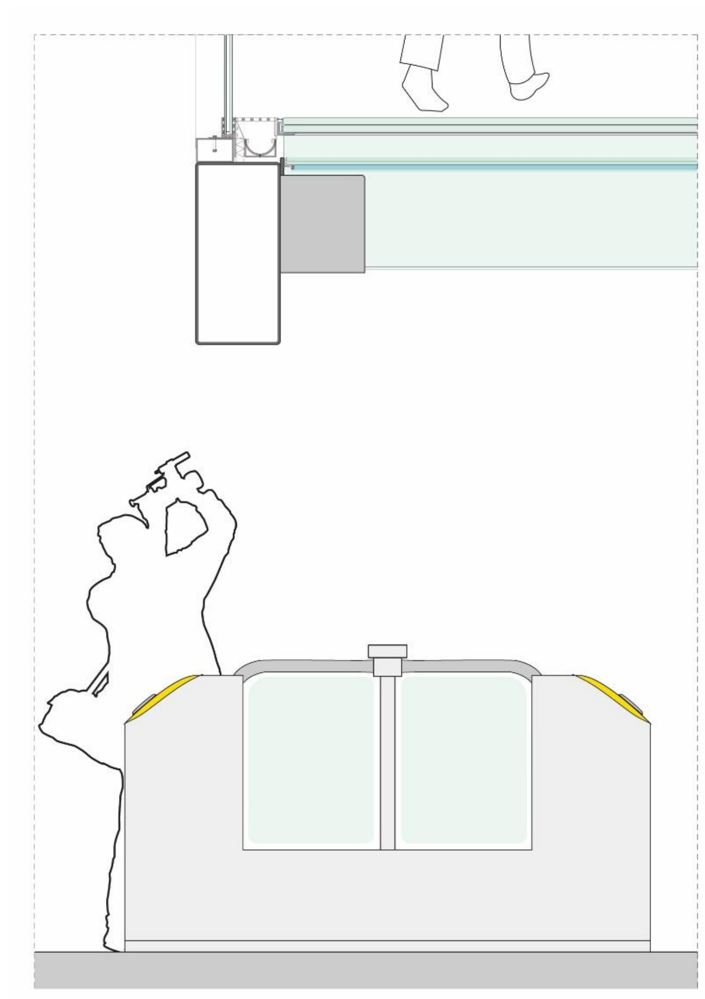


Figure 93 – Longitudinal section of the the glass beam to façade transition

Detailing

When we zoom in on the configuration of the glass elements we can see the implementation of the design recommendations in the floor build up. The use of laminated glass beams with interlayers support the laminated glass floor panels, the interlayer used is Sentryglas.

The more distinct feature is the separation between the two horizontal panels. The lower panel is a combined panel with a 8-8 mm safety glass laminate with a 15 mm intumescent interlayer underneath and covered by a sacrificial glass pane. In the case of fire, the intumescent interlayer expands creating an insulating layer. To allow for the expanding of the interlayer, the sacrificial glass pane may break without affecting the structural stability of the laminated 8-8 mm glass above.

The floor panels of the bus square, resting on top of the glass beam, is built up from 6-15-15 mm laminated safety glass. The 15-15 mm laminated glass uses SentryGlas interlayer, while the 6 mm a sealant which can be de-assembled in the case of fracture of the top layer. The 6 mm glass is not in place to act as structural element, it is placed on top of the floor panel to absorb impact and protect the two structural layers beneath.

The two horizontal glass panels are placed at a distance of each other to protect the top 1/3rd of the laminated glass beam from direct heating. In the case of fire the intumescent interlayers expand, wrapping the beam and lower glass panel with an insulating carbon char. The top part of the beam is kept relatively cool as was the case in the EMPA test.

The glass beam is a 12-12-12 mm laminated glass beam with a height of 350 mm. The bottom 2/3rds of the beam has a 15 mm intumescent interlayer on three sides of the beam. This interlayer is protected from moisture, damage and other influences to remain stable. The beam sits in a steel support shoe on the side of the spanning steel I-beams.

The images shown here are not the final details. The final details can be found in the appendix due to their size.

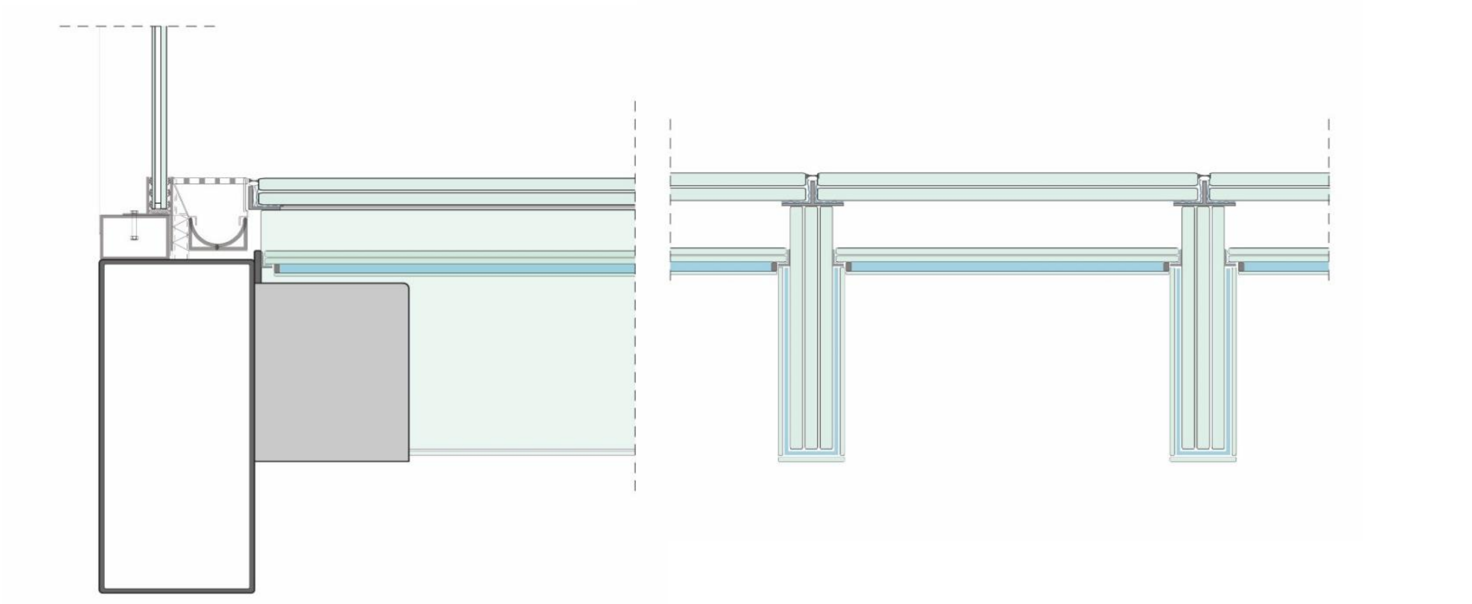
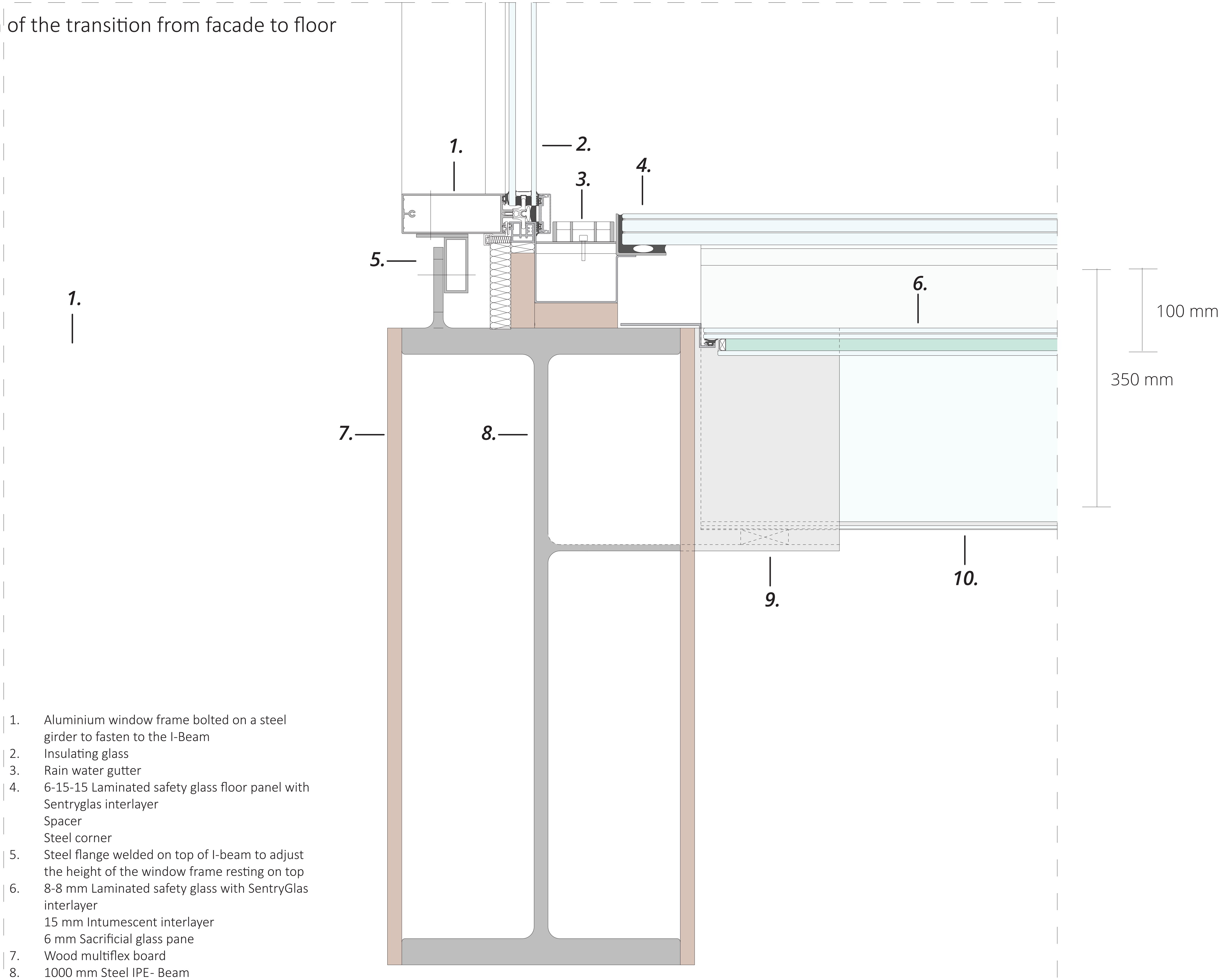


Figure 95 – On the left the first sketch of the façade and floor transition detail – Right a sketch cross section of the structural glass beams and floor panels

1 : 5 Details

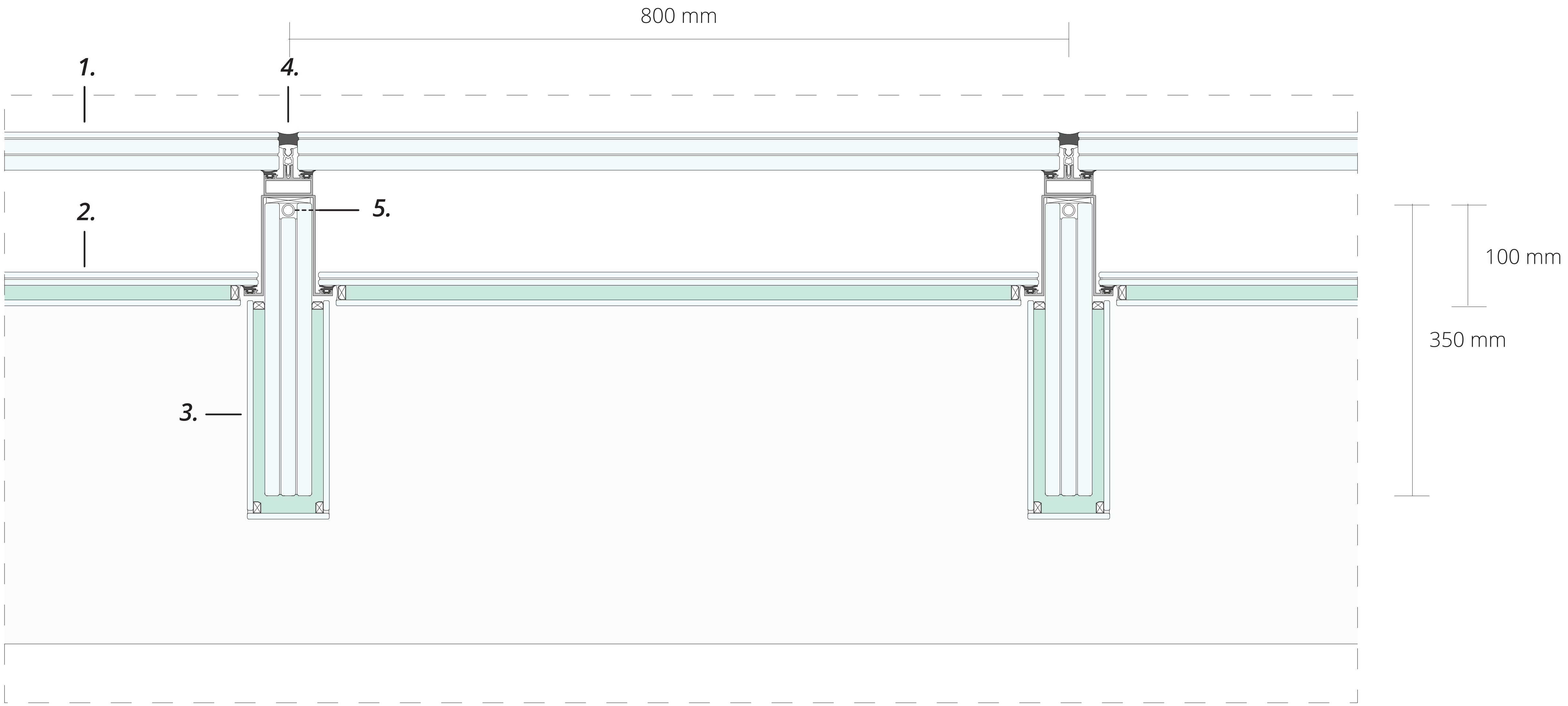
Corner longitudinal section of the transition from facade to floor



1. Aluminium window frame bolted on a steel girder to fasten to the I-Beam
2. Insulating glass
3. Rain water gutter
4. 6-15-15 Laminated safety glass floor panel with Sentryglas interlayer
   Spacer
   Steel corner
5. Steel flange welded on top of I-beam to adjust the height of the window frame resting on top
6. 8-8 mm Laminated safety glass with SentryGlas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
7. Wood multiflex board
8. 1000 mm Steel IPE- Beam
9. Steel shoe as glass beam support
   Spacer
10. Structural glass beam resting in steel shoe

1 : 5 Details

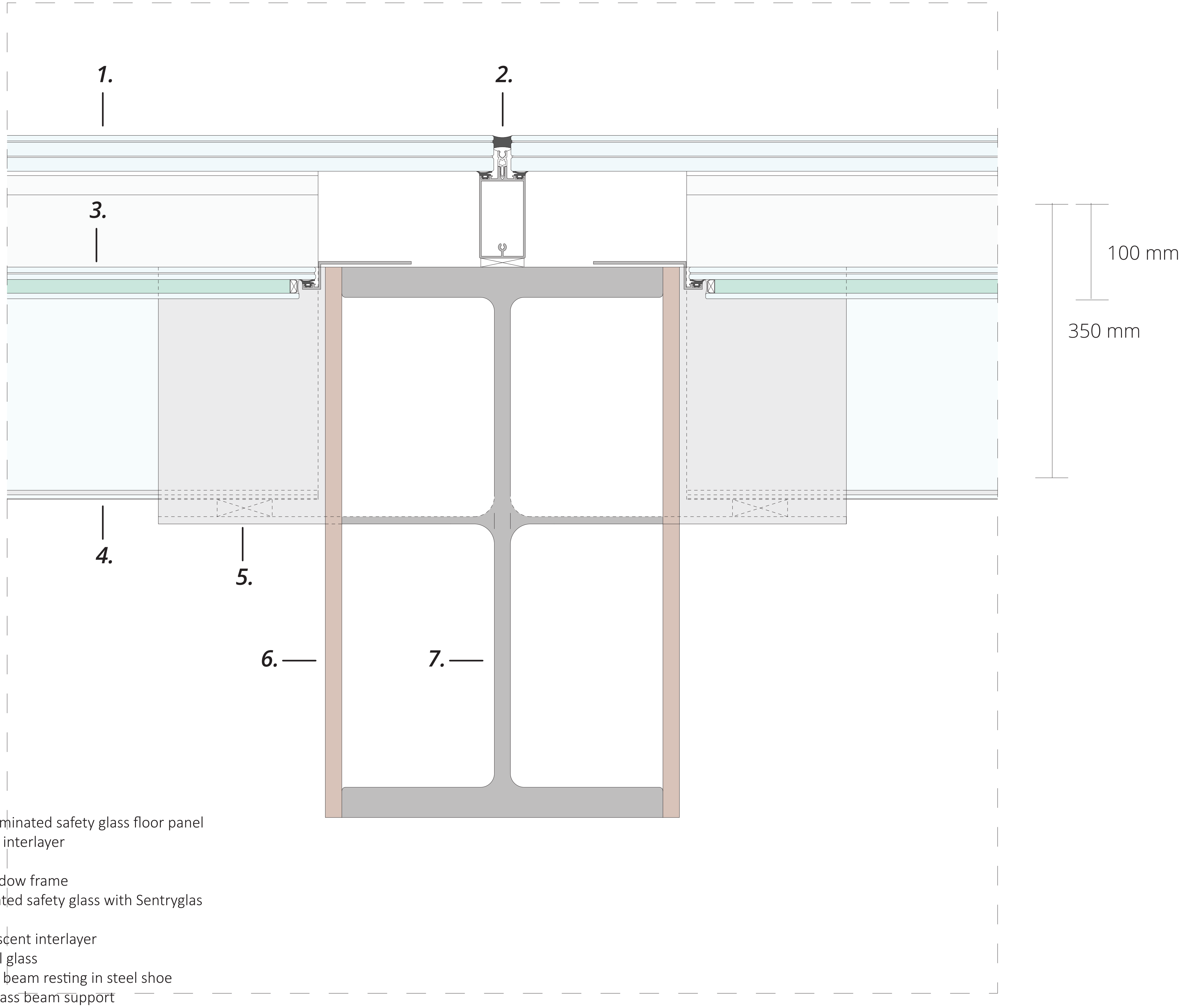
Cross section of two glass beams with spanning glass panels



1. 6-15-15 mm Laminated safety glass floor panel with Sentryglas interlayer
2. 8-8 mm Laminated safety glass with Sentryglas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
3. 6 mm Sacrificial glass pane
   15 mm Intumescent interlayer
   12-12-12 Laminated fully tempered glass beam
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
4. Silicon sealant
   Aluminium window frame
   Aluminium cap to support the intumescent panels
5. LED - lighting strip

1 : 5 Details

Cross section of the support detail between glass beams with aluminium window frame



1. 6-15-15 mm Laminated safety glass floor panel with Sentryglas interlayer
2. Silicone sealant
   Aluminium window frame
3. 8-8 mm Laminated safety glass with Sentryglas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass
4. Structural glass beam resting in steel shoe
5. Steel shoe as glass beam support
   Spacer
6. Wood multiplex board
7. 800 mm steel IPE beam

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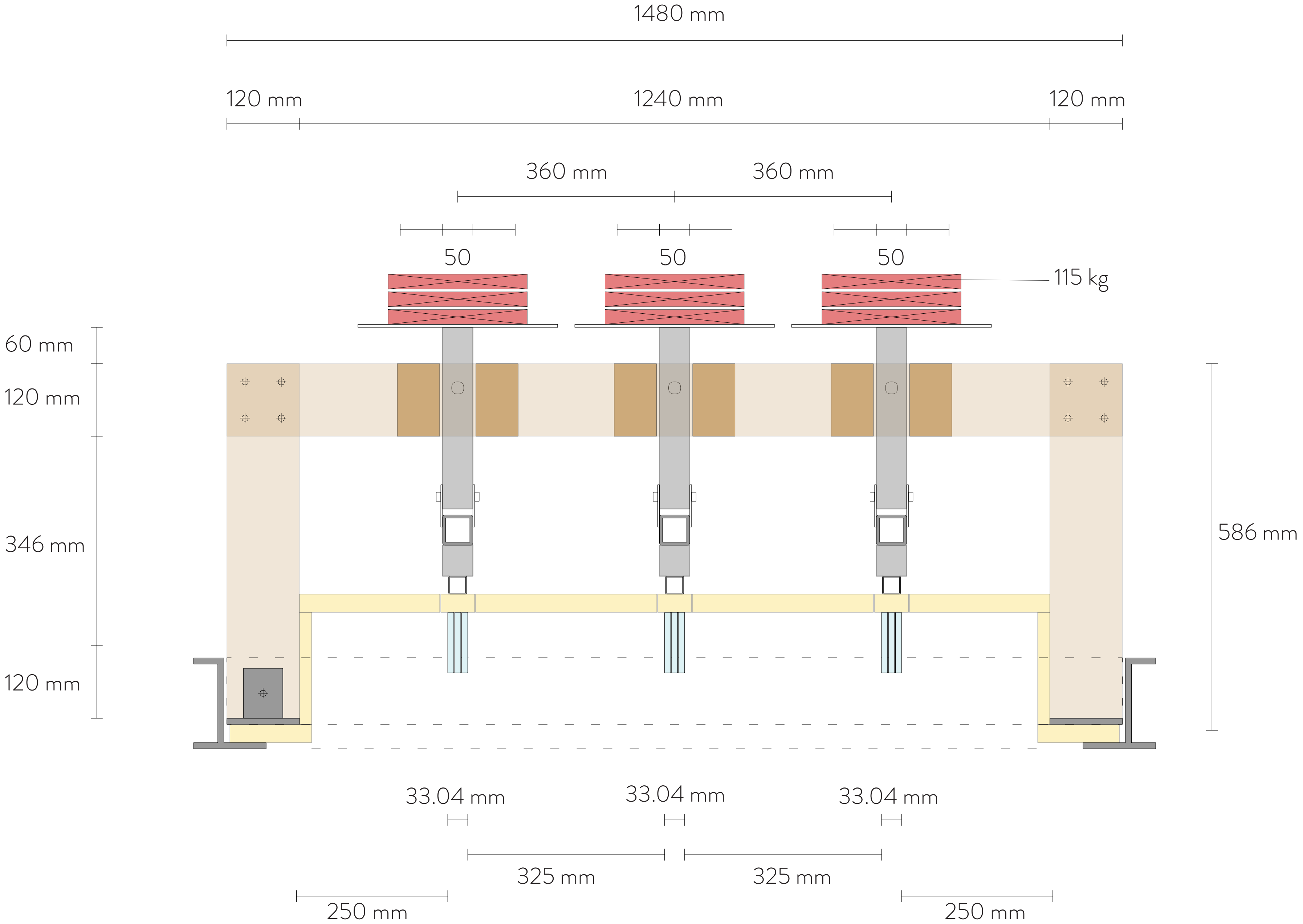
Appendix

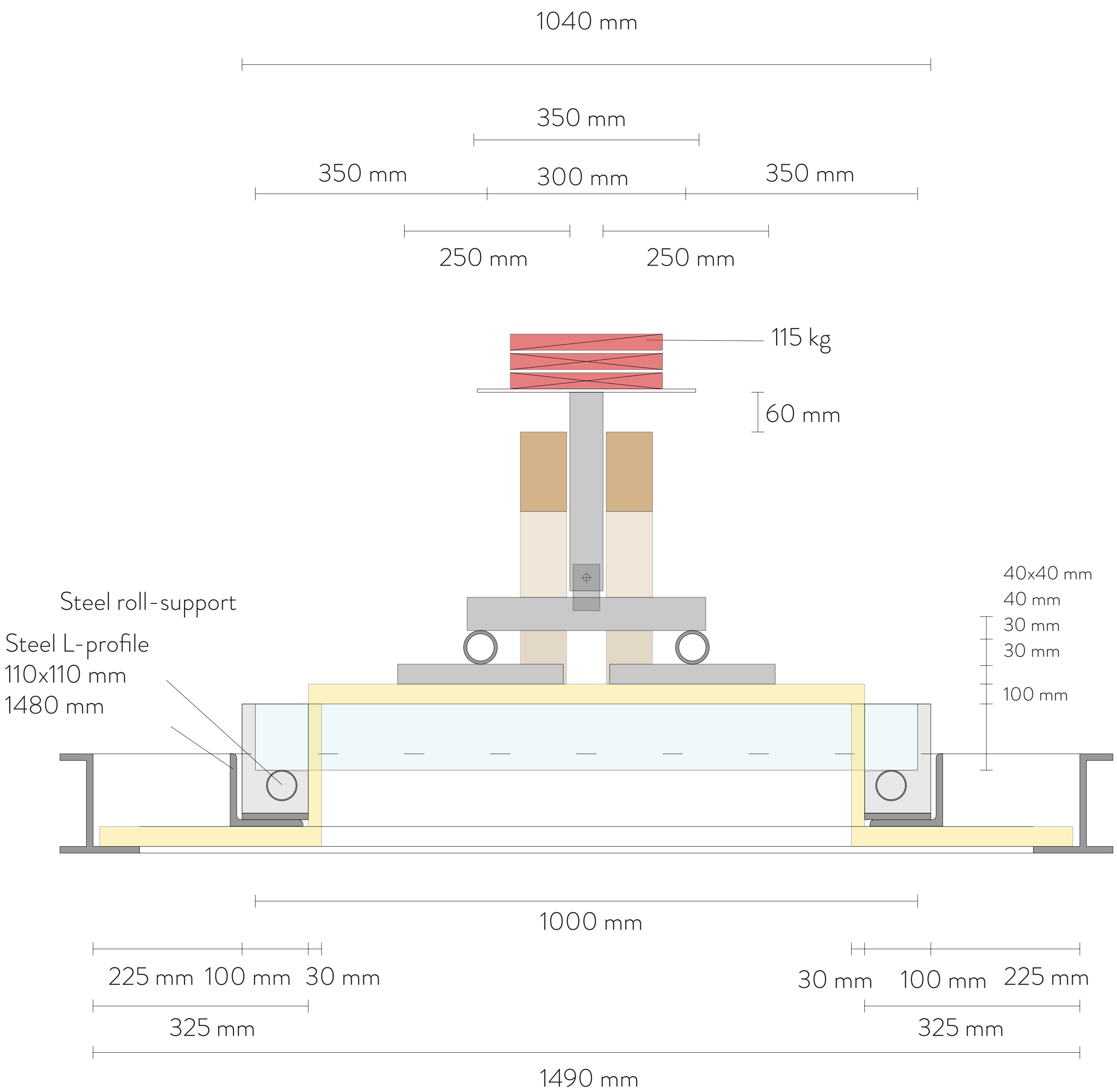
PVB Beams	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	First flame	Start Temp.
Annealed	1	Christian	Test PVB	x	AN PVB - pos 2	115 kg	NO		x	27.22
	2	Jelle	Test 1	x	AN PVB - pos 1	115 kg	Yes	Fracture (11min)	142 C	12.27
Heat Strengthened	3	Christian	Test PVB	x	HS PVB - pos 3	115 kg	NO		x	25.26
	4	Jelle	Test 1	x	HS PVB - pos 2	115 kg	NO		152 C	12.43
	5	Jelle	Test 4	3 cm HCA-TR	HS PVB - pos 1	115 kg	NO	Delayed heating	241 C	23.91
	6	Jelle	Test 4	2x 6 mm glas	HS PVB - pos 2	115 kg	(Yes)	Fracture (2min)	280 C	23.81
	7	Jelle	Test 4	10 cm HCA-TR	HS PVB - pos 3	115 kg	NO	Delayed heating	247 C	23.52
Fully Tempered	8	Christian	Test PVB	x	FT PVB - pos 3	115 kg	NO		x	21.74
	9	Jelle	Test 2	x	FT PVB - pos 3	115 kg	NO		93 C	15.65

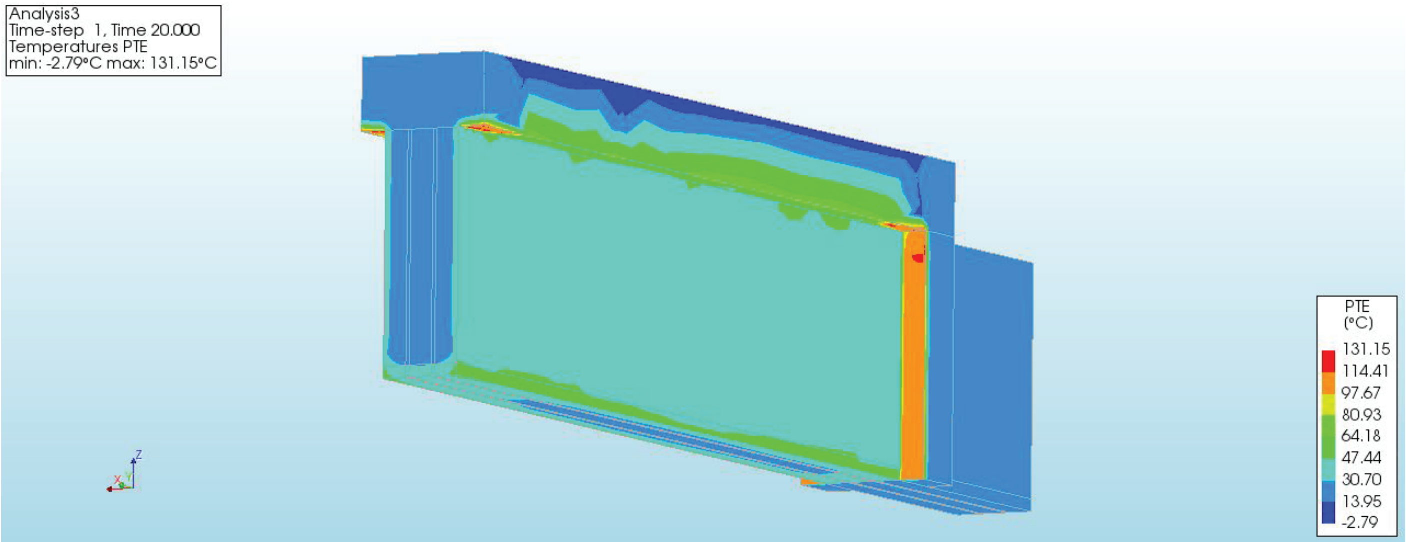
PVB Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
Annealed	1	34.68	742.43	39.83	N/A
	2	14.89	513.05		
Heat Strengthened	3	39.55	755.79	44.59	779.46
	4	17.23	599.20	19.56	661.67
	5	19.68	633.06	22.27	633.06
	6	14.60	549.30	17.68	720.74
	7	23.43	582.02	25.27	644.52
Fully Tempered	8	42.83	749.46	48.48	774.56
	9	16.23	585.56	18.54	639.05

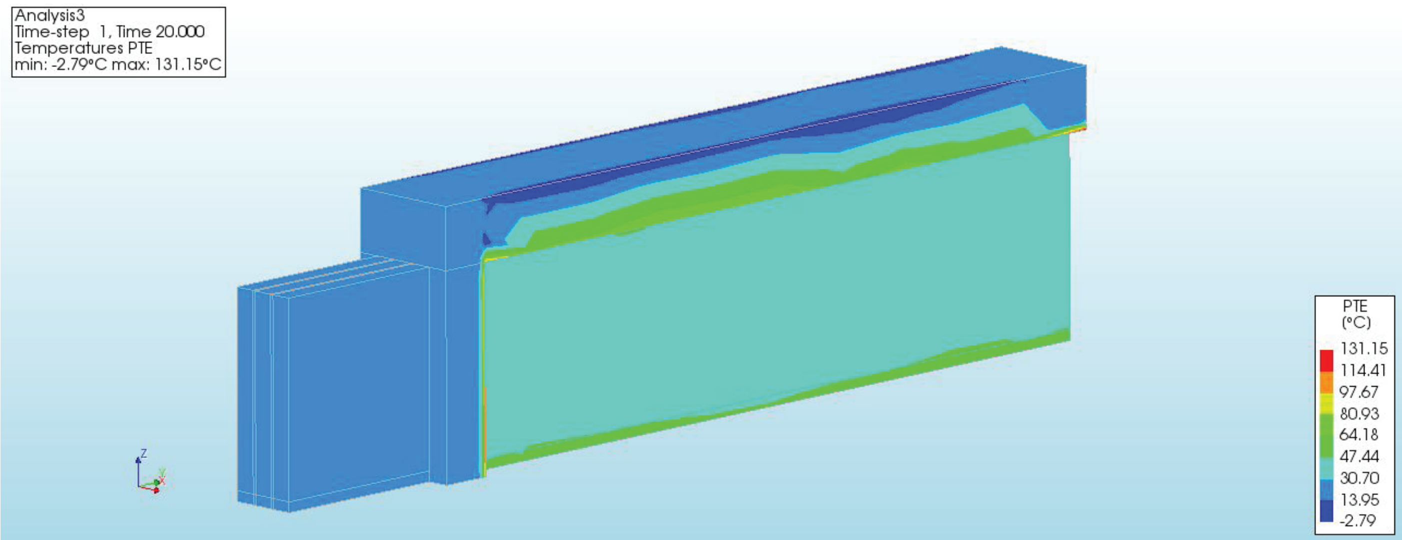
SG Beams	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	First flame	Start Temp.
Annealed	10	Christian	Test SG	x	AN SG - pos 1	115 kg	NO		x	25.23
	11	Jelle	Test 1	x	AN SG - pos 3	115 kg	Yes	Fracture(4min)	250 C	12.47
	12	Jelle	Test 3	x	AN SG - pos 2	250 kg	Yes	Fracture(8min)	x	12.03
Heat Strengthened	13	Christian	Test SG	x	HS SG - pos 2	115 kg	NO		x	25.25
	14	Jelle	Test 2	x	HS SG - pos 1	115 kg	NO		273 C	15.19
	15	Jelle	Test 3	x	HS SG - pos 3	250 kg	NO		362 C	11.92
Fully Tempered	16	Christian	Test SG	x	FT SG - pos 2	115 kg	NO		x	21.64
	17	Jelle	Test 2	x	FT SG - pos 2	115 kg	NO	Radiant heat effect	283 C	15.61
	18	Jelle	Test 3	x	FT SG - pos 1	250 kg	NO		335 C	12.30

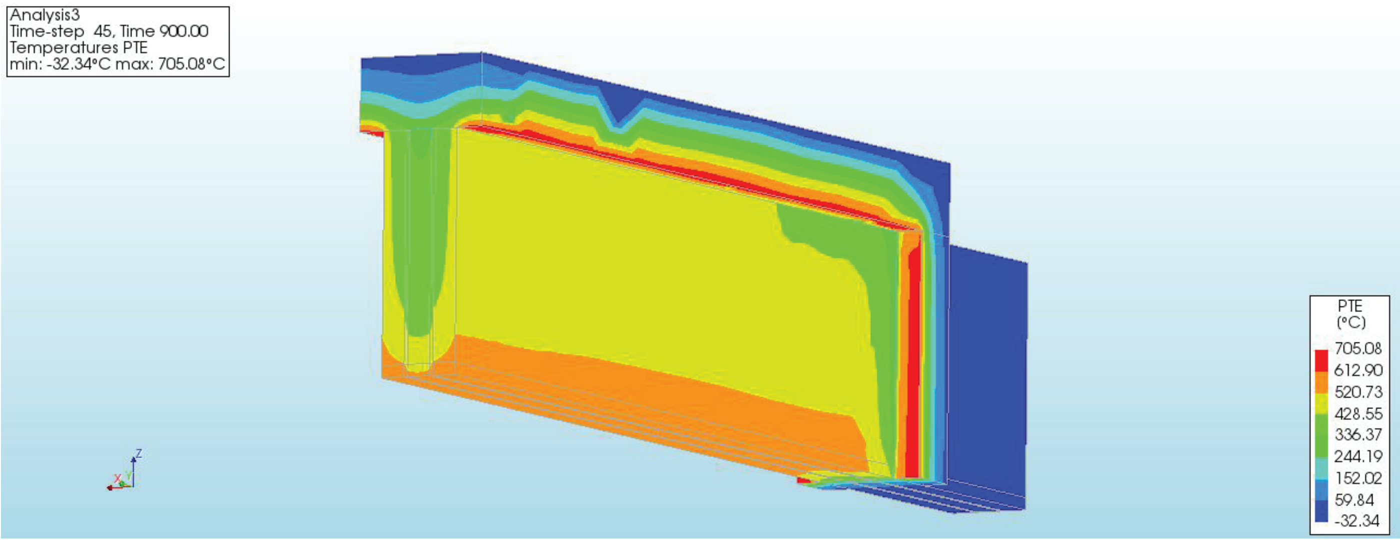
SG Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
Annealed	10	32.93	723.76	42.44	765.66
	11	7.81	219.71	8.14	230.46
	12	4.71	139.27	5.13	151.96
Heat Strengthened	13	41.75	760.00	47.81	769.90
	14	17.04	508.50	19.45	654.58
	15	15.71	571.36	18.63	625.56
Fully Tempered	16	48.04	751.42	54.13	762.26
	17	15.39	578.46	17.87	500.56
	18	17.46	514.92	20.29	600.48

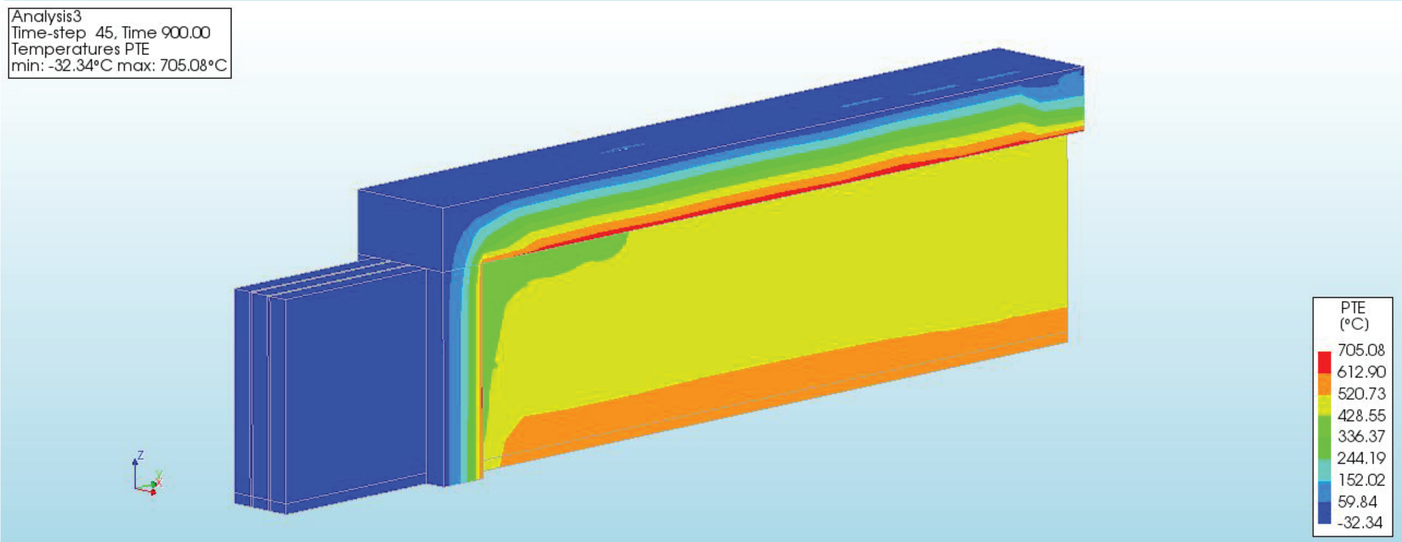

1480 mm
120 mm
1240 mm
120 mm
360 mm
360 mm
50
50
50
115 kg
60 mm
120 mm
346 mm
120 mm
586 mm
33.04 mm
33.04 mm
33.04 mm
325 mm
325 mm
250 mm
250 mm

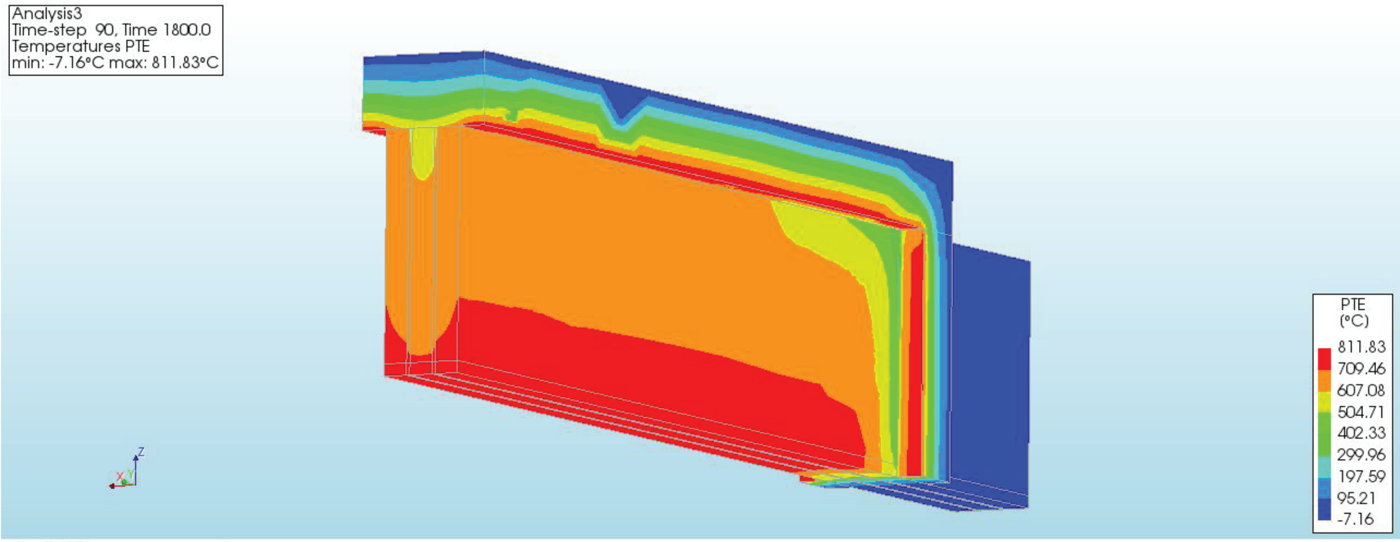

1040 mm
350 mm
350 mm
300 mm
350 mm
250 mm
250 mm
115 kg
60 mm
40x40 mm
40 mm
30 mm
30 mm
100 mm
Steel roll-support
Steel L-profile
110x110 mm
1480 mm
1000 mm
225 mm
100 mm
30 mm
30 mm
100 mm
225 mm
325 mm
325 mm
1490 mm

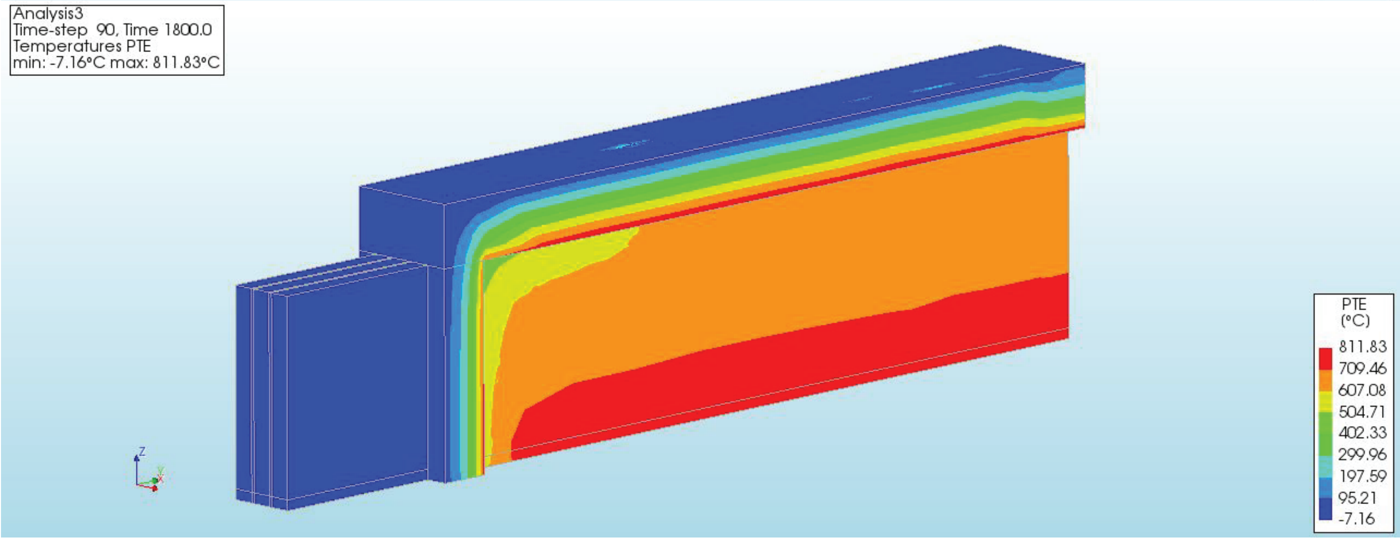

Analysis3
Time-step 1, Time 20.000
Temperatures PTE
min: -2.79°C max: 131.15°C
PTE
(°C)
131.15
114.41
97.67
80.93
64.18
47.44
30.70
13.95
-2.79
Z
X
Y


Analysis3
Time-step 1, Time 20.000
Temperatures PTE
min: -2.79°C max: 131.15°C
PTE
(°C)
131.15
114.41
97.67
80.93
64.18
47.44
30.70
13.95
-2.79
Z
Y


Analysis3
Time-step 45, Time 900.00
Temperatures PTE
min: -32.34°C max: 705.08°C
PTE
(°C)
705.08
612.90
520.73
428.55
336.37
244.19
152.02
59.84
-32.34
Z
X
Y


Analysis3
Time-step 45, Time 900.00
Temperatures PTE
min: -32.34°C max: 705.08°C
PTE
(°C)
705.08
612.90
520.73
428.55
336.37
244.19
152.02
59.84
-32.34
Z
Y


Analysis3
Time-step 90, Time 1800.0
Temperatures PTE
min: -7.16°C max: 811.83°C
PTE
(°C)
811.83
709.46
607.08
504.71
402.33
299.96
197.59
95.21
-7.16


Analysis3
Time-step 90, Time 1800.0
Temperatures PTE
min: -7.16°C max: 811.83°C
PTE
(°C)
811.83
709.46
607.08
504.71
402.33
299.96
197.59
95.21
-7.16