# Thin Glass

## A Study on the Applicability in Greenhouse Coverings

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## A Study on the Applicability in Greenhouse Coverings

by

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in partial fulfilment of the requirements for the degree of

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TU Delft

# Preface

Before you lies the final report of my graduation research, which has been written to fulfil the graduation requirements of the Building Engineering program, specialization Structural Design, at the Delft University of Technology. The subject of the research made it possible to combine my interest in glass design with the coordination of different specializations to come up with a practical solution to a current issue. I was engaged in the research from November 2016 to October 2017. During this time, a lot of people helped me with their support and feedback on the topic. I would like to use this opportunity to express my gratitude to those who have helped me to complete this graduation research.

First of all, I want to thank all the involved persons from the Delft University of Technology. I would like to thank the chairman of the graduation committee Rob Nijsse, for introducing me with glass as a structural material and for motivating me to think only in terms of solutions rather than problems. Special thanks go to my daily supervisor Christian Louter, for his expertise in glass structures and the numerous meetings we had. I would also like to thank Roel Schipper for his guidance, Max Hendriks for answering my questions about FE modelling and James O'Callaghan for sharing his expertise and creative advise. Furthermore, I would like to thank Kees Baardolf and Paul Vermeulen for their help with the practicalities of doing experimental work.

Secondly, I would like to show my appreciation to all of the companies that supported my research. Egon Janssen and Leo van der Knaap from TNO who helped me to obtain the right documents and to get into touch with relevant companies. Silke Hemming from the WUR for sharing the results of the light transmittance research for thin glass and answering all my questions related to this topic. Willem Snoeker from Achmea who helped me by sharing his knowledge about the very specific insurances for greenhouses. AGC and Anton Peters for providing the Leoflex panels for the experiments. Tjibbe van der Werf and Gerard Holsteijn from Boal for providing the aluminium framework and sharing their knowledge about greenhouse structures.

Furthermore, I would like to thank all the persons that made my time at the TU Delft unforgettable. My friends and roommates for listening to me talking about structures and for all the times they made me cry with laughter. Special thanks to my friends at Civil Engineering for the humongous amounts of coffee we drank and the fun we had during the breaks.

Finally, I would like to thank my family for their unconditional support and love during my whole life. You taught me to never give up and always follow your dreams. I especially want to thank Bob for his patience and faith in all of my choices. Your unconditional support during my studies and all foreign adventures always motivate me to live life to the fullest.

M.D.A. Mureau<br>Delft, October 2017

# Summary

Mankind has always been fascinated by the strength, transparency and brittleness of glass. Nowadays, glass is a commonly used material for façades and roofs. Recently even structural glass elements have been developed and the application of glass in structural elements is becoming more common. The ongoing development of new glass types and different production and processing methods resulted in the manufacturing of thin chemically strengthened aluminosilicate glass by AGC. Thin glass is mainly applied in the electronics industry, but the increased strength, optical properties, toughness, bending resistance and weather resistance make it a promising material for application in buildings.

The small thickness and large flexibility of thin glass make it necessary to increase the stiffness of the panels for application in large spans for building structures. A short exploratory study was performed for the determination of the definite research topic. Four distinctive stiffening options of thin glass panels were researched: air-inflating, twisting, tensioning and increasing the moment of inertia for flat panels. All four stiffening methods proved to be potentially interesting for further research. However, the application of thin glass in air-inflated, twisted and tensioned panels is more abstract than the application in stiffened flat panels. A realistic application for thin glass as flat panels can be found in the greenhouse industry to optimize the properties of greenhouse coverings.

The Netherlands is the globe's number two food exporter and more than half of the nation's land area is used for agriculture and horticulture. Research on the optimisation of greenhouse designs is a hot topic in the Netherlands in order to maintain this leading position. The greenhouse industry provides an appropriate application for flat thin glass panels, because of the possibility to increase both light transmittance and structural performance. The goal of the research presented in this report is to determine the feasibility of the application of thin chemically strengthened aluminosilicate glass in greenhouse coverings.

Numerous different greenhouse systems are developed all over the world, therefore the scope of the research was firstly defined for achieving a more explicit research. As a result, the research has been focused on the applicability of Leoflex glass with a thickness of 0.55 mm in a standardised Venlo system located in the Netherlands. Hereafter, the concept study was performed to investigate whether thin chemically strengthened aluminosilicate glass can be used for optimisation of greenhouse covering properties. The concept study was divided into four topics that are relevant for greenhouse designs: building physics, structural properties, structural behaviour and economics. Finally, the results of the research of these individual topics have been used for the structural design of a flat thin glass panel for application in a greenhouse covering.

The research on the light transmittance properties of thin glass has been conducted by the Greenhouse Technology team of the Wageningen University & Research. The (interim) results of this research showed that the hemispherical light transmittance of uncoated thin glass panels is 2% higher than that of the recently applied regular float glass. The research on the thermal transmittance properties showed that the application of thin glass results in values that are comparable to the values of regular float glass.

The investigation of the structural properties of thin chemically strengthened aluminosilicate glass was based on available literature and the material properties provided by the producer. The strength of glass is enormous when looking at the atomic level, however the strength is largely reduced by surface and edge flaws. Safety is of great importance for glass designs and the broad range of material quality results in a relatively low design value. For this research a characteristic bending tensile strength of 260 MPa has been assumed. However, the accuracy of this value and the testing procedure for the bending test of thin glass needs to be further researched. Moreover, the chemical treatment of thin glass is likely to result in a higher impact strength. However, further research is also recommended for the determination of the design impact strength of thin glass.

The structural behaviour of a thin glass panel in a greenhouse covering was investigated by executing both numerical and experimental analyses. First, simply replacing the regular float glass in the Venlo system by thin glass was studied by the use of finite element (FE) models and resulted in large deformations both in-plane and out-of-plane. The in-plane deformations of the edges were exceeding the maximum values according to the present Dutch design standards. These maximum values are related to the supporting width of the aluminium frame and exceeding the limits might cause the panel to slip out of the supporting frame. Therefore, it was recommended to stiffen the thin glass panel for flat application in a Venlo system. Subsequently, a variation study was performed to determine the most suitable stiffening method for application of a thin glass panel in a greenhouse covering. Multiple variants were designed and studied by numerical analyses. Experiments on small scale panels were conducted for the most promising variants. Hereafter, the results of the numerical and experimental analysis were compared. The results of the FE models and experiments were in general equivalent and it was assumed that the FE models could be used to predict the structural behaviour of flat stiffened thin glass panels. The numerical and experimental analysis of the sandwich structure variant resulted in the smallest deformations in x, y and z directions. However, the results of the IGU analysis also showed a large reduction of the deformations, but without the need of light blocking spacers in contrary to the sandwich panel. Not only the structural properties but also the building physics properties are important for greenhouse design. Therefore, the IGU panel turned out to be the most promising variant for future application of thin chemically strengthened aluminosilicate glass in greenhouse coverings.

The economic research showed that the application of thin glass in greenhouse coverings will result in an increased crop yield due to the better light transmittance. However, the energy yield will be comparable to that of the currently applied float glass. The costs for the transportation, maintenance and insurance will be reduced by the thin glass application. On the other hand, the material costs of thin chemically strengthened aluminosilicate glass are high and dictate the economical feasibility of the design at this moment. An economic feasible design for thin glass in greenhouse coverings can be achieved by a drop in the material price due to an increased demand. The execution of a more into depth economical feasibility study was recommended for taking into account all benefits and disadvantages of the application of thin chemically strengthened aluminosilicate glass.

As a main outcome of the concept study it was concluded that thin chemically strengthened aluminosilicate glass has a better light transmittance, higher bending strength and increased impact strength than regular float glass. This leads to a higher crop yield and lower costs for transportation, construction, maintenance and insurance which makes thin glass an attractive alternative. At this moment, however, the material costs are very high and the decreased thickness and increased flexibility resulted in a lower stiffness. It is therefore not likely that a single layer of uncoated thin chemically strengthened aluminosilicate glass will result in a feasible greenhouse covering design. Nevertheless, the use of thin chemically strengthened aluminosilicate glass can result in an optimised greenhouse covering design when applied as an insulating (IGU) panel.

It was recommended to conduct further research on both thin glass in general and the applicability of thin glass in greenhouse coverings. For thin glass in general, it was advised to look further into the exact material properties, influence of surface and edge flaws and the local buckling effects of perpendicular loaded plates. For additional research related to the applicability of thin glass in greenhouse coverings it was recommended to investigate the light transmittance properties of coated thin glass, the vulnerability of the panels to hail damage, the applicability of thin glass in different greenhouse systems and to conduct larger scale tests and a comprehensive economical feasibility study.

# Contents

# Nomenclature

## Latin Symbols

| | |
|---|---|
| $A$ | Area |
| $dz_{buck}$ | Change of mode deformation |
| $E$ | Young's modulus |
| $G$ | Permanent load |
| $h_i$ | Internal heat transfer coefficient |
| $h_e$ | External heat transfer coefficient |
| $h_t$ | Total conductance |
| $Q$ | Live load |
| $q_{load}$ | Evenly distributed load |
| $s$ | Total width edge seal |
| $S1$ | Resulting principal stress DIANA |
| $t$ | Thickness of the glass panel |
| $t_i$ | Interpane spacing thickness |
| $TX$ | Resulting deformation DIANA in x direction |
| $TY$ | Resulting deformation DIANA in y direction |
| $TZ$ | Resulting deformation DIANA in z direction |
| $U$ | Thermal transmittance |
| $w$ | Out-of-plane deformation |

## Greek Symbols

| | |
|---|---|
| $\alpha_{Staaks}$ | Buckling factor Staaks |
| $\eta$ | Haze |
| $\lambda$ | Wavelength |
| $\nu$ | Poisson's ratio |
| $\rho$ | Density |
| $\tau$ | Transmittance |
| $\tau_\alpha$ | Angular light transmission |
| $\tau_h$ | Hemispherical light transmission |
| $\tau_\lambda$ | Spectral light transmission |
| $\tau_p$ | Perpendicular PAR transmission |

## Abbreviations

| | |
|---|---|
| AGC | Asahi Glass Co. |
| ANG | Annealed Glass |
| AR | Anti-reflective |
| DOL | Depth of Layer |
| FE | Finite Element |
| FTG | Fully Tempered Glass |
| HSG | Heat Strengthened Glass |
| IGU | Insulating Glass Unit |
| PAR | Photosynthetic Active Radiation |
| PBA | Plate Bending Application |
| PC | Polycarbonate |
| PVB | Polyvinyl Butyral |
| SLS | Serviceability Limit State |
| TSSA | Transparent Structural Silicone Adhesive |
| ULS | Ultimate Limit State |
| UV | Ultra-violet |
| WUR | Wageningen University and Research |

# 1 Introduction

Glass has always been used by mankind and dates back before recorded history. Naturally occurring glass was already used a long time before people learned the production process of glass and started to make it by themselves. The earliest known glass objects are beads and in the beginning glass was mostly used for objects such as knives, arrowheads, jewellery and money. However, this glass was obsidian, black volcanic glass, and it took a long time before the technique for producing transparent glass was invented. The development of the glass production technique of glass blowing resulted in the use of glass in everyday used objects such as drinking glasses and from the 14th century glass was firstly used in buildings as lead glass was invented. From the 17th century the first glass sheets were produced to be used as windows. Hereafter the glass production process developed rapidly and is still ongoing. Nowadays, glass is commonly used in buildings for achieving high transparency and a controlled indoor climate. Recently, the transparency, durability and costs of glass in the building industry are becoming more and more important. Resulting in developments of new glass types and different production and processing methods.

In 2012 AGC unveiled Leoflex: "a chemically strengthened speciality glass for versatile applications". According to the press release of AGC Asahi Glass Co. (2012) Leoflex is "a chemically strengthened glass that is stronger than conventional soda-lime glass and is resistant to cracking". The reduced thickness of the glass enables a weight reduction in different applications such as solar panels, building materials and lightning. Thin chemically strengthened glass is mostly used in the electronics industry, but the application of thin glass and its weight reduction can also be beneficial for the building industry. However, at this moment, relatively little research is performed on the strength properties and application of thin glass in structures.

The application of thin chemically strengthened aluminosilicate glass in structures is therefore chosen as the topic of this research. The purpose is to firstly investigate different possibilities for the use of thin glass in the building industry based on structural properties. Hereafter one of those topics will be chosen and studied more into depth. The research and the accompanying results are shown in this report.

The structure of the report is as follows:

In **Part I** the research definition is presented by firstly showing a short exploration of different topics related to thin glass in the building industry in *Chapter 2*. At the end of this chapter a choice is made for the detailed topic of the research. Hereafter the research objectives and research question are presented in *Chapter 3*.

**Part II** describes the literature used for the research about glass in *Chapter 4* and greenhouses in *Chapter 5*.

The main part of the research is presented in **Part III** and is subdivided into six sections. First the boundary conditions and scope are defined in *Chapter 6*. Secondly, the building physics research and the resulting properties for thin glass are treated in *Chapter 7*. Thirdly, the structural properties for thin glass design are investigated in *Chapter 8*. Hereafter, a numerical and experimental research to the structural behaviour of thin glass in greenhouse coverings is executed in *Chapter 9*. Then, a study is performed to the economic feasibility for the application of thin glass in greenhouses in *Chapter 10*. Lastly, a structural design for a thin glass panel for application in a greenhouse covering is elaborated in *Chapter 11*.

Finally, the conclusions, *Chapter 12*, and recommendations, *Chapter 13*, are presented in **Part IV**.

# PART

Research Definition

# 2
# Topic Exploration

Thin glass is a relatively new material and the application possibilities for the building industry are, at this moment, not yet widely researched. Therefore it is important to firstly investigate the different application possibilities for thin glass with its according potentials and challenges. The exploratory study on possible research topics is presented in this chapter. Firstly, thin glass for the building industry is shortly treated with its advantages and disadvantages. This leads to the determination of potential applications of thin glass in the building industry. Hereafter, the potential application topics will be shortly explored one by one. The explanation of the topics and the conclusion of the feasibility study are presented in this chapter, while the full research is presented in Appendix B. Finally, a choice is made for the topic that will be used for the more into depth research.

## 2.1. Thin Glass

Glass has always been used by mankind and dates back to before recorded history. Early tribes discovered glass that was formed by nature, which eventually led to the development of the glass that we know nowadays (Rasmussen, 2012). Glass is used in multiple applications and everyday products. In the building industry the application of glass as a building material has increased over the last years. Nowadays, glass is not only used as cladding, but is also applied in structural components as shown in Figure 2.1.

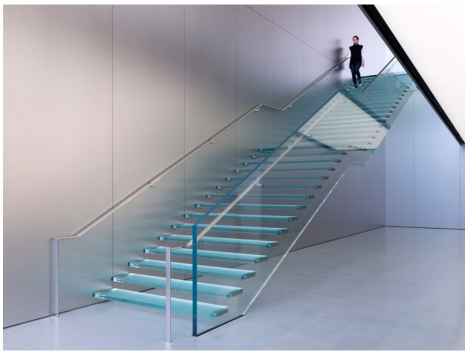


**Figure 2.1:** Structural glass in Apple store Hangzhou [Photography by Nigel Young, Foster + Partners]

**Figure 2.2:** Demonstration of the flexibility of thin glass [Photography by Corning]

The last years, frequent research is performed to get more insight in the mechanical behaviour and application possibilities of glass in the building industry. At the same time, the technical performance of glass as a building material increased due to technical developments. One of these developments is the fabrication of (chemically treated) thin glass that has a higher strength, larger flexibility and better optical properties than regular float glass. The improved strength and flexibility properties of thin glass provide new possibilities for the application of glass in structures. Thin glass is frequently used in the electronics industry, but relatively little research is performed on the strength properties and application of thin glass in structures.

### 2.1.1. Advantages and Disadvantages

AGC Leoflex is the type of thin glass that is considered in this research. The data sheet of AGC Leoflex glass is presented in Appendix A. From now on when “thin glass” or “Leoflex” is mentioned it is thin chemically strengthened aluminosilicate glass while the mentioned “regular regular” glass is tempered soda lime glass. Thin glass has a number of advantages and disadvantages when compared to regular soda lime glass.

The main advantage of thin glass is that the chemical strengthening process results in a higher strength than the tempered soda lime glass. The increased strength provides the opportunity to use thinner panels which are easier to bend and will result in more lightweight solutions. The chemical strengthening process also increases the scratch resistance and weather resistance of the panels, while the chemical composition of the aluminosilicate glass ensures high optical clarity.

However, the structural properties that are relevant for the structural calculations such as bending and tensile strength are not yet known. A safe estimation of these values has to be used for the calculations, which results in the use of conservative values and thus not the maximum potentials of the thin glass can be used. An other disadvantage of the application of thin glass is the reduced stiffness due to a decreased moment of inertia and the higher costs per square meter of glass.

### 2.1.2. Potential Applications

The application of thin glass has both advantages and disadvantages as explained above. For the use in the building industry, a distinction can be made between two main application possibilities based on the advantages of thin glass, namely:

- Using the flexibility by allowing big deformations of the glass in order to create an adaptive shape;
- Using the increased strength properties by stiffening the glass in order to create a static shape.

The choice is made to focus on the application of thin glass in a static shape for the topic exploration. Thin glass needs to be stiffened for application in a static shape due to its small thickness and high flexibility. The four different stiffening possibilities for thin glass that will be further investigate are:

- Air pressurising
- Bending
- Increasing moment of inertia
- Stretching

## 2.2. Exploration Potential Topics

Relatively little research had been published on the stiffening of thin glass panels for application in the building industry. This is why the choice is made to first shortly investigate four potential topics for research on this subject, to check which of these topics is the most promising for further research. The choice for the main research topic of this report is based on this topic exploration and is presented at the end of this chapter.

Four potential research topics for the application of thin glass are formulated, based on the four different ways to stiffen a thin glass panel.

- Air-inflated panels
- Twisted panels
- Stiffened flat panels
- Tensioned panels

The sections below treat shortly the feasibility study and the corresponding conclusions of the four potential research topics. The literature overview and the results of the more detailed feasibility study are presented in Appendix B.

### 2.2.1. Air-inflated Panels

Schueller (1996, p. 702) states that *"films are thin, flexible sheets of homogeneous material (e.g. clear vinyl, polyester, polyethylene) with the same properties in all directions"*. According to this definition, thin glass can be considered to be a film and that it might be possible to use thin glass in a membrane structure. The two most commonly applied membrane structures are: tension structures and pneumatic structures. The latter one is the basis of the first topic for which the feasibility will be explored.

Pneumatic structures can be subdivided in two different types: air-supported and air-inflated, see Figure 2.3. An air-supported structure has an entirely pressurised internal volume, while an air-inflated structure has an interior space that remains at atmospheric pressure and only the space between dual membranes is pressurised (Schueller, 1996). The air-inflated system will be the most suitable system to apply thin glass due to the safety and producing possibilities.

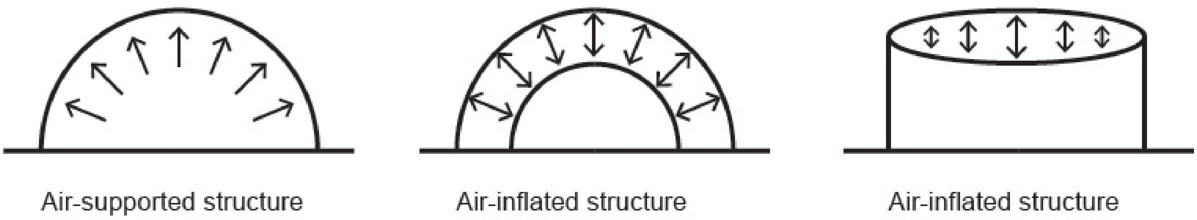



**Figure 2.3:** Difference between an air-supported and air-inflated structure

Despite the fact that thin glass can be considered a film, there is no certainty that an air-inflated structure of thin glass is feasible. As far as known, no (comprehensive) research is yet performed on the possibilities of using air pressure to stiffen thin glass elements. It is necessary to shortly explore the possibilities and limitations of using thin glass in an air-inflated panel, in order to determine the feasibility of this application of thin glass. This exploration is presented in Appendix B and consists of a short literature overview and short research.

#### Conclusion Feasibility Study

As a result of the literature study and the exploration of the topic as shown in Appendix B, the following conclusions can be drawn.

Disadvantages of using thin glass for air-inflated panels:

- The use of thin glass results in a higher dead load and subsequently the need of a larger foundation, while one of the advantages of the use of a membrane structure, is the use of light foundations.
- An air-inflated structure made of thin glass has to be divided in separate panels, because thin glass cannot yet be produced in the same (large) dimensions as foils.
- The air-pressure should be large for sufficient curvature of the glass panels. The double curving with a higher air-pressure results in large initial tensile in-plane stresses.
- One of the advantages of "traditional" pneumatic structures is the modest investment and transportation costs. At this moment, thin glass is very expensive and therefore an air-inflated structure of thin glass will also be very expensive.

Advantages of using thin glass for air-inflated panels:

- Thin glass is better resistant to the environmental influences than traditional films. Therefore, no special coatings are needed when glass is used and a longer serviceability life time of the air-inflated structure can be reached.

- The optical properties of thin glass are better than those of traditional used films, which results in a higher transparency.

### 2.2.2. Twisted Panels

Glass can either be hot or cold bended. The cold bending process takes place at ambient temperature, while a temperature of about 600 °C is required for the hot bending process. Hot bended glass requires the reheating of the glass and the fabrication of form work. This is not necessary for cold bending and therefore the costs of cold bending are lower. Regular float glass can be both hot and cold bended while hot bending is not yet possible for thin glass. A disadvantages of cold bending is the introduction of stresses in the glass pane which limits the bending radii that can be achieve with cold bending. Thin glass has a high bending resistance and can easily be cold bended to small radii. The minimum bending radius for thin glass can directly be related to its thickness, due to the almost flawless results of the surface by the overflow process. However, due to the spring back effect it is needed to fix the cold bended glass panels in the required position.

Glass can be cold bended in two different configurations: single or double curved, as shown in Figure 2.4. Research has already been performed on the cold bending of regular float glass and these glass panels are applied in various buildings. In 2016, two master research projects were executed at the Delft University of Technology on the possibilities of using cold bended thin glass in façade elements. Simoen (2016) investigated the possibilities of using cylindrical curved thin glass panels in a static façade panel, while Silveira (2016) looked into the possibilities of using thin glass panels in an adaptive façade.

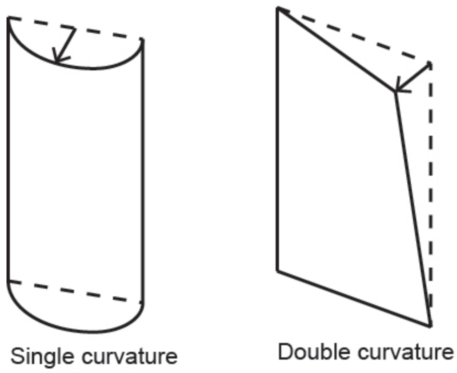



**Figure 2.4:** Single curvature vs. double curvature thin panel

As far as known, no comprehensive research is yet performed on the possibilities of the application of cold formed twisted thin glass panels. It is necessary to shortly explore the possibilities and limitations of using thin glass in a cold formed twisted panel, in order to decide the feasibility of this application of thin glass. This exploration is presented in Appendix B and consists of a short literature overview and short research.

#### Conclusion Feasibility Study

As a result of the literature study and the exploration of the topic as shown in Appendix B, the following conclusions can be drawn.

Disadvantages of using thin glass for twisted panels:

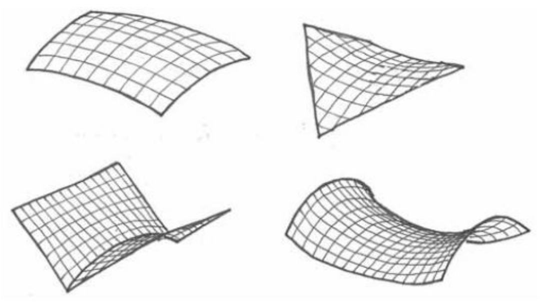
- Buckling of the plate will occur at smaller corner displacement due to the decreased thickness. This results in distorted reflections and curved edges, which can cause problems for the connections.
- Relatively large steel frames are needed in order to stiffen the glass and keep it in the cold bended or twisted configuration. This reduces the transparency.
- Lamination of the panels is necessary for safety reasons. This results in smaller bending radii with larger initial stresses.

Advantages of using thin glass for twisted panels:

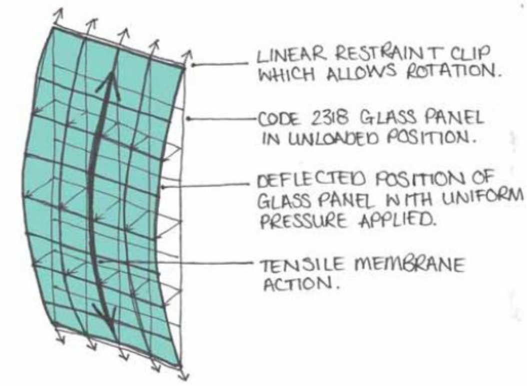
- Higher bending strength and smaller thickness, so larger curvature can be achieved (smaller bending radii).
- Thin glass is more transparent and has a higher surface quality due to the overflow production process that ensures that the glass doesn't have contact with any solid. The glass has a higher optical quality because it doesn't contain iron and this results in a curved panel that will look more transparent.

### 2.2.3. Tensioned Panels

The first two possibilities for stiffening the panel, inflating and bending, increase the out-of-plane stiffness by changing the element by either adjusting the geometry or adding material thickness. It is also possible to keep the element unchanged, but adjust the structural system for creating stiffness. An adjusted structural system that is already used in the building industry is a tensile membrane structure. In this structural system, a fabric is able to resist the loads by applying an initial axial tensile force to the membrane. Thin glass panels can be considered as a stiff fabric, because they are flexible and behave in the same way as a stiff fabric (Lambert and O'Callaghan, 2013). It is therefore interesting to investigate the possibilities to stiffen a glass façade of thin glass elements by making a tensile membrane structure, see Figure 2.5.



**(a)** Potential shapes for tensile membrane structures




**(b)** Example built-up tensile membrane panel

**Figure 2.5:** Possibilities for thin glass tensile membrane panels (Lambert and O'Callaghan, 2013)

Thin glass is likely to have a higher tensile strength than regular float glass due to the chemical treatment. The higher tensile strength of thin glass will make it a suitable material to use in a tensile membrane panel. However, the exact values of the tensile strength of thin glass are not yet determined in experiments. Different testing procedures are investigated in Neugebauer (2016), but no specific results for the tensile strength were presented in this paper.

In the glass performance day proceeding of 2013 a couple of potential applications for thin high strength glass are treated. The application of a tensile membrane structure is mentioned by Lambert and O'Callaghan (2013). In this proceeding, there is stated that *"initial investigations have indicated that connections to the glass are likely to govern the design of such (tensile membrane) structures"*, but also that the *"topic would benefit from further investigation"* (Lambert and O'Callaghan, 2013, p.97). As far as known, no further comprehensive research is yet performed on the possibilities of applying thin glass elements in a tensile membrane structure. The accompanying topic exploration is presented in Appendix B and consists of a short literature overview and short research.

#### Conclusion Feasibility Study

As a result of the literature study and the exploration of the topic as shown in Appendix B, the following conclusions can be drawn.

Disadvantages of using thin glass for a tensioned façade:

- The ultimate tensile strength of glass has to be verified with experiments.

- The tensile strength of glass is depending on the imperfections of the surface and edges of the sheet. Thin glass is sensitive for scratches or small damages of the surface that will lower the tensile strength, due to the small depth of the pre-tensioned layer.
- The pretension has to be applied by the connections and therefore the connections are likely to be governing for the strength. No bolted connections are possible in thin glass due to stress concentrations. Therefore the connections need to be glued and thus the glue is likely to be the governing structural element of the façade.

Advantages of using thin glass for a tensioned façade:

- Lightweight solution, which leads to a reduction of the supporting structure dimensions.
- Tensile strength thin glass is higher than regular float glass, so a higher tensile force in the panels can be achieved.

### 2.2.4. Stiffened Flat Panels

The structural system was changed for the three previous topics to create thin glass panels with sufficient stiffness for application in the construction industry. However, it is also possible to stiffen a panel by either increasing the moment of inertia of the panel itself or changing the supporting conditions while maintaining the flat shape of the panel, see Figure 2.6. The increase of the moment of inertia will ensure a larger out-of-plane stiffness and thus a more stable element. The moment of inertia can be increased by lamination or the use of a substructure to create a sandwich panel. The supporting conditions can increase the stiffness of a flat panel be changed by using clamped supports, pre-tensioning or a supporting substructure.


**Figure 2.6:** Stiffening flat plate: left increasing moment of inertia, right change supporting conditions

There is already some research performed on the lamination of thin glass. Overend et al. (2014) carried out research to laminated hybrid-glass units that aim to outperform conventional laminated glass units. Leonhard et al. (2015) performed research for laminating thin chemically strengthened glass to regular float glass for application in automotive wind shields. The first panels of this hybrid-laminate are already applied in the Ford GT Supercar.

A possible relevant application of stiffened thin glass panels can be found in the greenhouse industry. The greenhouses for the protected agriculture are designed in order to maximise the harvest. Glass is often chosen as covering due to its strength, optical properties, low maintenance and high lifetime, but glass is also a brittle material and its vulnerability to catastrophic losses caused by hail is a predominant disadvantage. The use of thin glass in greenhouse coverings is likely to decrease the losses due to hail damage, while the optical properties will be similar or even increased. It is even likely that the supporting structure can be minimised due to the lower weight of thin glass and this would be beneficial for the solar interception. The orientation and shape of the covering is important for greenhouses and therefore flat glass panels are preferred. This means that the thin glass panels should be stiffened in order to be used in greenhouses.

As far as known, no comprehensive research is yet performed on the possibilities of stiffening thin glass for the use in greenhouse covering. It is necessary to shortly explore the possibilities and limitations of using thin glass in a stiffened flat panel, in order to decide the feasibility of this application of thin glass. This exploration is presented in Appendix B and consists out of a short literature overview and short research.

#### Conclusion Feasibility Study

As a result of the literature study and the exploration of the topic as shown in Appendix B, the following conclusions can be drawn.

Disadvantages of using thin glass for stiffened flat panels:

- The stiffness of the thin panel will be reduced due to the smaller thickness and a solution should be found to stiffen the panel for application in large spans.
- The light transmittance of the thin glass is not yet researched in relation to the crop growth.
- The structural material properties of thin aluminosilicate glass are not yet scientifically researched and thus no design values are present.

Advantages of using thin glass for stiffened flat panels:

- Impact strength is likely to be higher than the impact strength of the traditional used glass panels.
- A longer life-time compared to the use of plastics for greenhouse coverings.
- Lightweight solution which results in the reduction of the supporting structure which increases the light transmittance.

## 2.3. Choice

The general conclusion of the previously executed topic exploration is that the four topics all have potentials for further research. Each of the topics has both advantages and disadvantages for the use of thin glass over the use of regular float glass. It can be stated that the application of thin glass has a couple of factors, such as weight reduction and increase of strength properties, that are beneficial for all four of the topics.

However, the application of thin glass in air-inflated, twisted and tensioned panels is more conceptual than the application of thin glass in stiffened flat panels. The application of thin glass in stiffened panels can be a solution to an existing problem, while the application of thin glass in the other topics will be mainly a method to demonstrate state-of-the-art developments of glass in the building industry.

The application of stiffened flat thin glass panels in greenhouses can have multiple potential benefits:

- The application of thin glass in greenhouses might reduce the hail damage problems, due to the expected increase of the impact strength compared to regular float glass.
- The weight reduction of the panels might lead to a smaller supporting structure for all of the applications of thin glass. However, a reduction of the supporting structure in a greenhouse is not only beneficial for the aesthetics, but it leads to an increase of the yield by decreasing the solar interception.
- Single panes of glass are used in the greenhouse coverings at the moment. The application of stiffened flat thin glass panels in greenhouses will increase the safety due to the possible lamination of the panels. This might not be necessary according to the codes in the greenhouses that are used for the growth of crops, but this safety increase is beneficial for the greenhouses that are used for retail areas.
- The Netherlands is the globe's number two food exporter and more than half of the nation's land area is used for agriculture and horticulture (Viviano, 2017). The research on the optimisation of greenhouse designs is a hot topic for maintaining this leading position and many companies and research institutions are performing research in this field of activity. This results in the fact that it might be possible to co-operate with a research institution such as the WUR (Wageningen University and Research) in order to investigate the light transmittance influence of the application of thin glass.

The combination of the relevance, collaboration possibilities and benefits of the application is decisive in the consideration and reasoning for the topic choice. This is why the choice is made to perform further research for the application possibilities of thin chemically strengthened aluminosilicate glass panels in greenhouse coverings.

# 3

# Thesis Statement

The topic exploration and the choice for the topic that will be further analysed during the graduation research were presented in the previous chapter. This chapter treats the thesis statement of the graduation research. Firstly, the main problem is defined and presented. Secondly, the research objective is formulated. Hereafter, the research question and sub questions are given. Lastly, the approach for the research is shown.

## 3.1. Problem

The world population is expanding rapidly and is estimated to be 9.7 billion by the year 2050 (United Nations and Affairs, 2015). The agriculture sector faces a great challenge: providing sufficient food and other necessities for this growing world population. However, the possibilities for the expansion of arable land are limited and the task of providing enough food is even more challenging due to the more extreme weather conditions as a result of the climate change (Ponce et al., 2014). Protected agriculture is used for cultivation of high-value horticultural crops in greenhouses and allows farmers to grow crops on plots where traditionally agriculture is not viable. Protected agriculture offers many advantages such as: large increases in product quality, high water productivity, lower production costs and year-round production.

In the Netherlands, protected agriculture is becoming more of an importance due to the limited space available for traditional agriculture. Consequently, an increase of horticulture area under glass can be seen. The greenhouses for the protected agriculture are designed to maximise the harvest. A traditional covering of the greenhouses used in the Netherlands is a single layer of glass, because it is a strong and transparent material. However, glass is also a brittle material and subject to shattering. Last years, more extreme weather conditions were present in the Netherlands due to the climate change (Rosenzweig et al., 2001). A summer storm in June 2016 caused a huge amount of hail damage to the greenhouses in the southern part of the Netherlands. The media showed devastating images of the damage (see Figure 3.1) and estimated the loss in only the agricultural sector to be a total of at least one hundred million Euro.

**Figure 3.1:** Impression of hail damage summer 2016 (retrieved from: www.sierteeltnet.nl, photographer: R. Kloppenburg)

Glass is often chosen as covering due to its strength, optical properties, low maintenance and high durability. Although, glass is also a brittle material and its vulnerability to catastrophic losses caused by hail is a predominant disadvantage. Thin chemically strengthened aluminosilicate glass is developed and frequently used in the electronics industry. This type of glass has better strength properties, a higher bending strength and is likely to have a higher impact strength than regular float glass (see Chapter 8). It is likely that the use of thin glass in the greenhouse covering will increase the impact strength of the covering, which results in a decrease of the losses due to hail damage. However, the strength and light transmittance properties of thin aluminosilicate glass are not yet determined. It is required to investigate the light transmittance, economics, structural properties and behaviour of thin chemically strengthened aluminosilicate glass panels, before arriving at conclusions for the applicability of this material in greenhouse coverings.

## 3.2. Research Objective

The objective of the research is to determine the applicability of thin chemically strengthened aluminosilicate glass in greenhouse coverings, by taking into account the building physics, structural properties, structural behaviour and economics.

## 3.3. Research Question

The research will be shaped by the main research question and the complimentary sub-questions. The sub-questions will be answered one by one during the research, the main question will be answered when all of the sub-questions are answered.

The main research question is:

*Can thin chemically strengthened aluminosilicate glass be used to improve the properties of greenhouse coverings regarding the buildings physics, structural properties, structural behaviour and economics?*

The sub-questions that originate from the central question are:

- How does the application of thin chemically strengthened aluminosilicate glass influence the light transmittance and thermal transmittance of the greenhouse covering?
- What are the structural properties of thin chemically strengthened aluminosilicate glass?
- What is the structural behaviour of thin chemically strengthened aluminosilicate glass for different load cases when applied in greenhouse coverings?
- In which way can a thin chemically strengthened aluminosilicate glass panel be designed so that the structural integrity of the system is maintained during external loading?
- Which economic benefits does the application of thin chemically strengthened aluminosilicate glass in greenhouse coverings have compared to the regular float glass?

## 3.4. Approach

The following approach is used for the total research. First the potentials of thin chemically strengthened aluminosilicate glass are explored. The choice for a static or adaptive shape is made and hereafter a short exploratory research to four different research topics is conducted. One of the topics is chosen that is going to be thoroughly investigated during the graduation research. Then a concept study is performed for the chosen topic and application. The concept study consists out of four different topics and these topics will all be individually investigated. The concept study is completed by the preparation of a structural design for a thin glass panel for application in a greenhouse covering. Finally, the results of the concept study are assembled, the conclusions are drawn and recommendations for further research are presented. A visualisation of the research approach is shown in Figure 3.2.

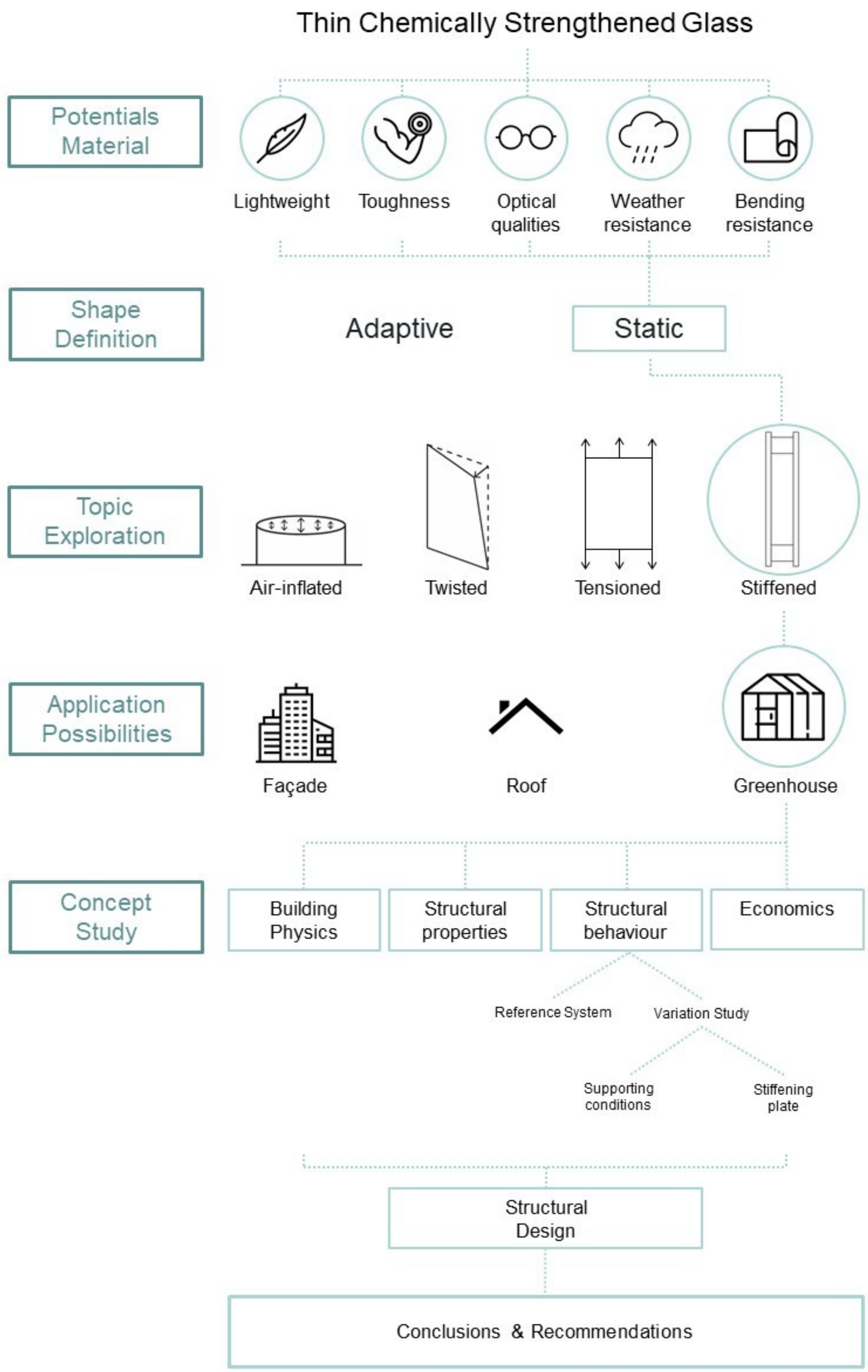



**Figure 3.2:** Flowchart of the used approach for the research

# PART II

Theoretical Framework

# 4
# Glass

This chapter treats the relevant background information about the material glass and the more recently developed thin glass. Firstly, the glass properties such as the chemical composition and material properties are shown. Then the different production techniques are presented.

## 4.1. Glass Properties

This section gives an overview of the properties of glass. This includes the chemical composition and the material properties.

### 4.1.1. Chemical Composition

A glass or amorphous solid is an inorganic product of the cooling down of a molten material without crystallization. The difference between an ordinary solid and glass is that an ordinary solid has a crystalline structure, while glass has a disordered arrangement of molecules which is similar to the arrangement in a liquid, as shown in Figure 4.1.

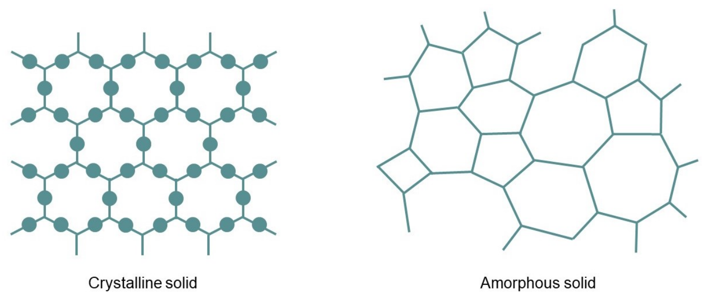



**Figure 4.1:** Structures of a crystalline solid (left) and an amorphous solid (right)

The transition of an amorphous solid between liquid and solid state does not take place at one precise temperature, but over a certain range. The temperature at which the glass solidifies is called the glass transition temperature and is about 530 °C (Haldimann et al., 2008, Chapter 1).

The transparency of glass is the result of the molecular configuration caused by the cooling of the molten material. The electrons in glass molecules are strictly confined to particular energy levels, unlike regular solids. This confinement ensures that the molecules cannot absorb the radiation in the bandwidths of visible and near infra-red. The energy passes straight through the molecules, which results in the transparency of glass. However, short infra-red wavelengths can go through the molecules, but the wavelengths are changed the instant it hits another object. This results in the fact that the infra-red light can no longer pass the glass, thereby heating the inside space. The photons in glass can change energy level due to UV light and therefore UV light is absorbed, making glass to be opaque under UV light. (Haldimann et al., 2008, Chapter 1)

Glass consists out of three basic types of ingredients: formers, fluxes and stabilizers. The glass former is the key component and in most glasses silica ($SiO_2$) is used. Fluxes can be added to lower the melting temperature and stabilizers are added to make glasses stronger and more durable. The most common types of glasses are soda lime silica glass, borosilicate glass and aluminosilicate glass. Table 4.1 shows the chemical composition of these glasses. The soda lime silica glass is commonly used for regular float glass, the borosilicate glass for the construction of reagent bottles and the aluminosilicate glass for the making of thin glass.

**Table 4.1:** Chemical composition of soda lime silica, borosilicate and aluminosilicate glass (Haldimann et al., 2008)

| | | Soda lime silica glass | Borosilicate glass | Aluminosilicate glass |
|---|---|---|---|---|
| Silica sand | $SiO_2$ | 69-74% | 70-87% | 62% |
| Calcium-oxide (Lime) | $CaO$ | 5-14% | - | 8% |
| Soda | $Na_2O$ | 10-16% | 0-8% | 1% |
| Boron-oxide | $B_2O_3$ | - | 7-15% | 5% |
| Potassium-oxide | $K_2O$ | - | 0-8% | - |
| Magnesia | $MgO$ | 0-6% | - | 7% |
| Alumina | $Al_2O_3$ | 0-3% | 0-8% | 17% |
| Others | | 0-5% | 0-8% | - |

### 4.1.2. Material Properties

Glass is a typical brittle material and has no plastic behaviour, this means that the material fails suddenly without giving warning signs such as yielding or the formation of small cracks. This behaviour makes it hard to predict the failure point of a glass element.

The difference in chemical composition, shown in Table 4.1, results in different physical properties. The most important physical properties of soda lime silicate glass and aluminosilicate glass are presented in Table 4.2.

**Table 4.2:** Physical properties of soda lime silica glass and aluminosilicate glass (AGC Electronics America, 2016)

| | Soda lime silica glass | Aluminosilicate glass | |
|---|---|---|---|
| Young's modulus | 73,000 | 74,000 | $MPa$ |
| Density | 2500 | 2480 | $kg/m^3$ |
| Poisson's ratio | 0.21 | 0.23 | $-$ |
| Vickers hardness | 533 | 595 | $kgf/mm^2$ |
| Glass transition temperature | 550 | 604 | $°C$ |
| Softening point | 733 | 831 | $°C$ |
| Annealing point | 554 | 606 | $°C$ |
| Strain point | 511 | 556 | $°C$ |
| Refraction index | 1.52 | 1.51 | $-$ |

For the strength of glass it is important to consider not only the material properties, but also the physical condition of glass. The theoretical value for the tensile strength of a sheet of glass will in practice be reduced due to surface flaws, notches and cracks (Veer et al., 2010). The strength properties of glass will be treated more into depth in Chapter 8.

## 4.2. Production Techniques

The production of glass consists of two parts: the on-line and off-line production. The different production techniques are treated in the following sections.

### 4.2.1. On-line Production

There are several different techniques available for the production of glass: blowing, floating, casting, extracting, down drawing and overflowing. The most used production technique for regular glass in the building industry is floating, while the thin glass is produced by the floating, down drawing or overflowing technique. The separate techniques for regular glass and thin glass are treated in the sections below.

#### Regular Glass

The float process was introduced in 1959 by the glass manufacturer Pilkington. The floating technique is currently the most used manufacturing process for glass due to the major advantages of low cost, wide availability, optical quality and available production sizes. The glass that is produced with the floating technique is called float glass and is produced in large manufacturing plants that operate continuously all year round. The floating technique consists basically out of seven steps (see Figure 4.2): mixing, melting, floating, coating, annealing, inspection and cutting.

First, the raw materials are weighed and mixed together and the mixture is melted in a furnace at a temperature of approximately 1550 °C. The molten glass is then poured onto a shallow pool of molten tin at a temperature of 1200 °C. The atmosphere in which the glass is poured consists out of hydrogen and nitrogen to prevent oxidation of the tin. Tin is used for the pool, because of its large temperature range of its liquid physical state and its high specific weight which ensures that the glass mixture will float on top of the tin bath. The glass floats on the tin and spreads out, forming a smooth flat surface with continuous thickness, this part of the process is giving the name to float glass. The speed of the rollers on both sides of the bath determines the thickness of the glass (2-25 mm). During the floating the temperature decreases from 1200 °C to 600 °C. Hereafter the optional metal-oxide coating can be applied with the spray pyrolysis technique. Then the glass is gradually cooled in the annealing lehr. The gradually cooling is necessary to prevent the induction of residual stresses in the glass. Hereafter, the glass is inspected with an optical laser to check for any flaws. Finally, the glass is cut in pieces with a dimension of 3.21 x 6.00 m. The imperfections recognized by the optical laser are removed during the cutting.

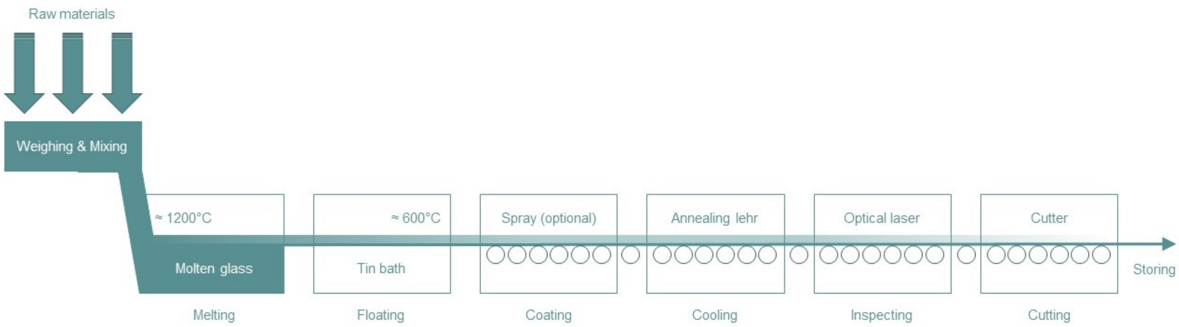



**Figure 4.2:** Visualisation of the Pilkington production process for float glass

#### Thin Glass

Glass with a thickness of 0.55 mm up to 2.0 mm can be defined as thin glass and as ultra-thin glass when the thickness is lower than 0.55 mm. Thin glass can be produced by three different processes: the micro-float process, the overflow-fusion process and the down draw process.

The micro-float process is a variation on the previously explained floating process that is used for the production of regular glass. This process can produce a glass thickness of approximately 0.7 mm. However, the maximum width that can be achieved with this process is 2.4 m.

The overflow-fusion process is based on the overflow principle that was originally conceived by Corning in 1964 as a method for manufacturing automotive wind shields. At that time the market for this production process was almost non existent, but this changed in the ’80s when thin glass needed to be produced for LCD screens. This new demand for thin glass has led to the further development of this technique. The process starts the same as the floating process with the weighing, mixing and melting of the raw materials. The molten glass is then poured into a v-shaped bath until it is filled and overflows at both sides (see Figure 4.3). The molten glass streams down the sides of the v-shaped bath and comes together at the bottom where the two flows combine to one flow. The resulting molten glass flows down vertically by gravity while cooling down without contacting any surface. When the plate is sufficiently cooled and stiff enough, the plate is cut and stored.

The down draw process is inspired by elder techniques and has been already patented in the 1970s. However, like the overflow-fusion process, the market was too small at that moment and the technique is later optimised for the production of thin glass. The process is similar to the overflow-fusion process, the difference is that the molten glass is not flowing down due to the gravity but that it is pulled down out of a furnace through an orifice. The glass is already annealed when it leaves the orifice and is ready to been cut in panels. The down draw process has the possibility to create thin glass rolls that have a length of over 100 metres.

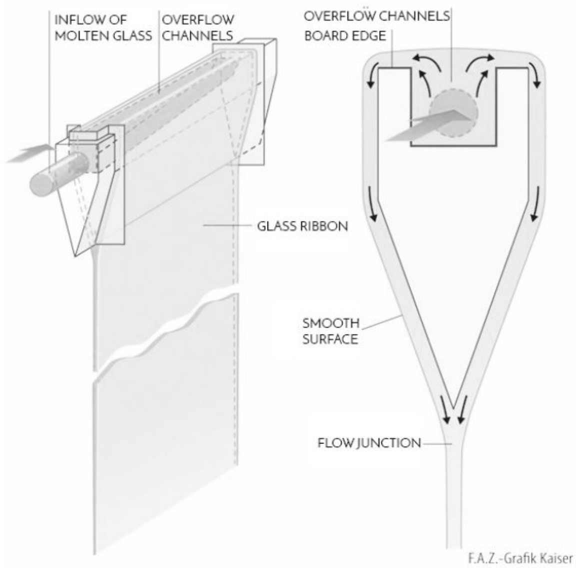



**Figure 4.3:** Overview of the overflow-fusion process (Silveira, 2016)

### 4.2.2. Post Production Processing

The cut glass panels are often processed after the manufacturing of the glass to produce products that meet the particular shape, performance and appearance requirements. This is called post production processing or off-line processing and may include: pre-stressing, grinding and cutting, thermal bending, lamination or coating.

#### Pre-stressing

Glass is a strong material, but the strength is strongly depending on imperfections in the surface. The material glass has the same behaviour as concrete: it is strong in compression, but weak in tension. The technology of pre-stressing of glass is developed to increase the strength qualities and to decrease the imperfection sensitivity. Pre-stressing creates a favourable residual stress field: tensile stress in the core and compressive stress in the surfaces. The core does not contain flaws and is thus resistant to the residual tensile stresses. The compressive stress in the surfaces reduces the imperfection sensitivity, because the tensile stress in the surface should overcome the residual compressive stress before the cracks can grow. Three methods can be used to pre-stress the glass: toughening, heat strengthening and chemical strengthening. The glass which has no pre-stress is called annealed glass. The breakage pattern of annealed (non pre-stressed) glass, heat strengthened and toughened glass is shown in Figure 4.4.

The toughening technique is the oldest technique and is based on the principle of the Prince Rupert's Drop. The result of the toughening is called fully tempered glass. The method consists of the heating of the glass

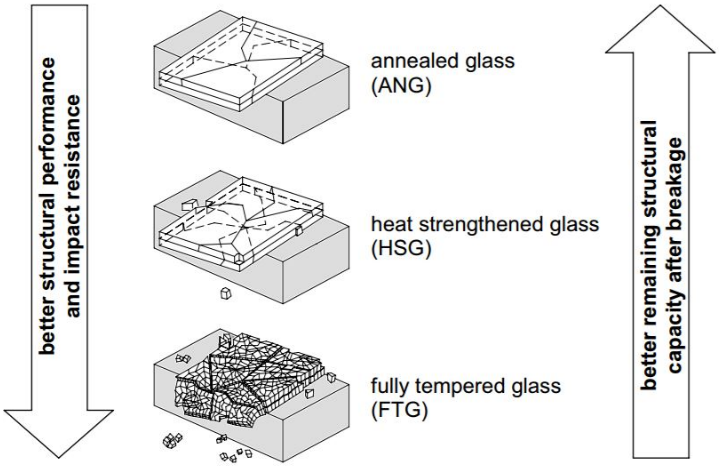



**Figure 4.4:** Breakage pattern of annealed, heat strengthened and toughened glass (Haldimann et al., 2008)

to approximately 620-675 °C in a furnace, after which it is cooled rapidly (quenched) by air jets. The rapid cooling induces tensile forces in the core and compression forces in the surfaces as explained previously.

The heat strengthening technique is similar to the toughening technique. The only difference is the speed in which the glass is cooled down after the heating. The glass is cooled down slower during the heat strengthening, which results in smaller residual stresses in the material. The difference between the two techniques is visible in the breaking pattern of the sheets. Toughened glass breaks in a lot of small pieces, while heat strengthened glass breaks in larger pieces and is more suitable to be used in laminated structural applications.

The chemical strengthening technique produces a different residual stress profile than the toughening and heat strengthening techniques. The difference is mainly in the thickness of the affected zone as can be seen in Figure 4.5. The glass is chemical strengthened by putting the panel in a bath of a saline solution with a temperature of 500 °C. For soda lime glass, the sodium ions in the surface are exchanged by the potassium ions in the saline solution. For aluminosilicate glass, the lithium ions are exchanged by sodium ions in the bats. The potassium and sodium ions have a bigger volume than resp. the sodium and lithium ions and this introduces the compressive stress at the surfaces. The Depth of Layer (DOL) is an important property for chemically strengthening of glass. A higher DOL results in a higher impact and scratch resistance. The DOL that can be achieved with soda lime glass is low due to the high availability of non-bridging oxides. Aluminosilicate glass has a high amount of alumina which reduces the number of non-bridging oxides, making it more convenient for chemical strengthening. The chemical strengthening method is more suitable for thin glass due to the thinner compressive layer and relative high DOL. Chemical strengthened glass has a similar breaking pattern as annealed glass due to the low tensile stresses in the core. This is why chemically treated glass should be laminated when used in the building industry.

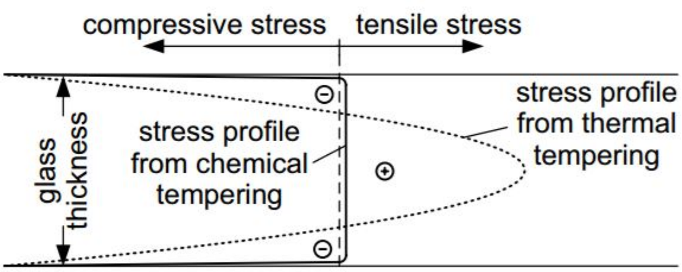



**Figure 4.5:** Residual stress profiles obtained by thermal and chemical strengthening (Haldimann et al., 2008)

### Grinding and Cutting

The produced glass panels are cut to make panes that can be transported to the building site. The cut edges are grinded to reduce the imperfections in the edges that are present due to the cutting. Veer et al. (2010) stated that the edges of the glass influence the strength properties of the glass plate and therefore the accuracy of the edge treatment is important. The cutting, grinding and drilling has to be performed before the heat threatening of the glass, but it can be performed after the chemical strengthening due to the low elastic energy in the core of the glass. However, the strength near the cut will decrease when it is performed after the chemical strengthening.

### Thermal Bending

Curved glass can be produced by heating the panels and then pushing the panel into a mall by a weight (or its own weight) after which it cools down and stays in the curved shape, this process is called thermal bending. Small bending radii that can be created with this technique, however this technique requires precision and custom made moulds. At the moment it is possible to combine the thermal bending with the thermal strengthening of the glass. It is also possible to chemical strengthen the thermal bended glass panel, an advantage of this is that the chemical strengthening is not influenced by the shape of the glass. Hot bending is not yet possible for thin glass.

### Lamination

The laminated panel is made by putting an interlayer in-between two glass panels. The package is put in an autoclave in which the interlayer is attached to the glass panels by the increasing pressure and temperature. Glass that is applied in the building or automotive industry is often laminated for safety reasons. The broken pieces of a laminated element will stick to the interlayer and so no damage will occur due to falling glass pieces. There are different kind of interlayers that can be used for lamination, the two most common types are: Polyvinyl butyral (PVB) and Sentryglas.

### Coating

Three different kind of coatings can be applied on soda lime silica glass: hard coating, semi soft coating and soft coating. The coatings can be applied to improve the optical, thermal and electrical performance of a glass pane. Hard coatings are commonly applied using a chemical vapour deposition and are placed on the exterior of the glass. Soft coatings can be applied by various processes such as dipping and chemical or physical vapour deposition, however they can only be placed between two planes of laminated glass or in insulated panels. Semi hard coatings are produced in a vacuum process with three different methods: thermal evaporation, cathode evaporation and magnetically reinforced vacuum metallizing.

# 5
# Greenhouse

The previous chapter evaluated the background information of the properties and production process of glass. This chapter treats the background information about greenhouses. Firstly, the properties of light relevant for greenhouses are treated. Hereafter, the aspects of greenhouse coverings such as materials and design requirements are presented. Then the main subjects regarding the greenhouse supporting structure are introduced. Finally, the essential aspects of insurances for greenhouses are shown.

## 5.1. Light

Natural light is one of the key factors for the growth and development of plants and crops. The building materials that are necessary for plant growth are produced from light, water and $CO_2$ by the photosynthesis process. The photosynthesis process is mainly determined by the photosynthetic active radiation (PAR) part of the spectrum in which a spectral distribution in accordance with the sensitivity curve of the crop is present (Hemming et al., 2004). However, the sunlight that is necessary for the crop production will always be influenced by the covering material of the greenhouse. The main concepts of light that are important for the greenhouse design are discussed in the following section.

### 5.1.1. Electromagnetic Spectrum

The sun emits radiation in the form of electromagnetic waves. This extra-terrestrial solar radiation is filtered by the atmosphere of the earth and changes to global radiation before it reaches the earth. The global radiation contains radiation of the wavelengths between 300 and 3,000 nm. Radiation with wavelengths between 3,000 and 10,000 nm is not directly emitted by the sun, but is thermal radiation (Giancoli, 2008). An overview of the electromagnetic spectrum is presented in Figure 5.1 .

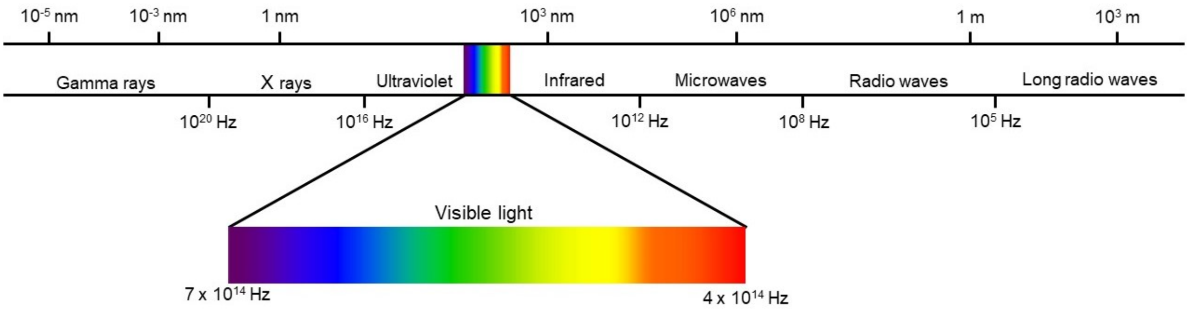



**Figure 5.1:** Electromagnetic spectrum

Only a small part of the global radiation is visible to the human eyes, this lies in the wavelength range of 380-780 nm. This part is called the "visible light" and corresponds to the colours blue, green, yellow, orange and red. A part of the visible light is used by plants for photosynthesis. This part with wavelengths between 400 and 700 nm is therefore called the photosynthetic active radiation (PAR). The ultra-violet part of the radiation, 300-400 nm, is the part of the global radiation with the highest energy level and can be divide in UV-A (315-400 nm) and UV-B (300-315 nm). A small part of the UV radiation is used by plants for photosynthesis and growth. The near infra-red radiation, 700-3,000 nm, is the part of the solar spectrum that is barely used by plants (Hemming et al., 2004).

### 5.1.2. Direct vs. Diffuse

Global radiation consists out of a direct and a diffuse radiation part. The direct radiation part of the global radiation is the solar radiation that reaches the earth's surface directly from the sun without being reflected. This radiation enters the greenhouse covering with the angle of incidence, which is determined by the position of the sun. The diffuse radiation is the part that is scattered by the atmosphere before it reaches the greenhouse covering.

Not only the radiation can be diffuse, but also the greenhouse covering material can be diffuse. The diffusivity of a greenhouse covering material is called the "haze" of the material. The haze is important for the crop growth and is dependent on the surface structure and pigments present of the material. The haze varies widely for different kind of materials, but a material is called a diffuse material when the haze is larger than 50%.

Diffuse light is able to penetrate deeper into the plant canopy in comparison to direct light, according to Hemming et al. (2014). The direct light stays primarily at the top levels of the canopy, while diffuse light is penetrating the canopy and stimulating growth, as shown in Figure 5.2. At high irradiation levels, diffuse greenhouse coverings result in better light distribution, lower crop temperature, decreased transpiration and increased photosynthesis and growth. Due to the presence of clouds for the largest part of the year, it can be stated that the light transmission of diffuse light is the determining factor for crop growth in the Western part of Europe. For example, in the winter season 75% of the incident radiation is diffuse, while this is only 25% in clear conditions. In general is diffuse light favourable for crop production and can result in a production increase of 8-10% for cucumber.

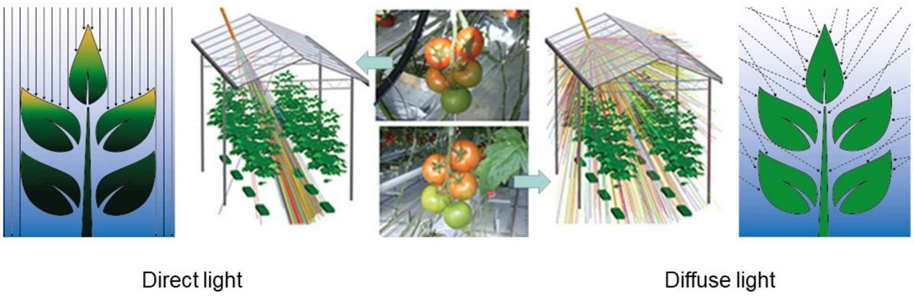



**Figure 5.2:** Effect of light penetration direct and diffuse light in greenhouse, image adjusted from WUR and Hortidaily

### 5.1.3. Perpendicular vs. Hemispherical Light Transmission

Two different types of light properties can be distinguished related to the light transmittance of greenhouses: perpendicular and hemispherical light transmission. The perpendicular light transmission is the transmission parallel to the normal of the surface and is primary intended for product comparison. The hemispherical light transmission is the transmission of light for all angles of incidence.

Since perpendicular light almost never occurs on greenhouse roofs, hemispherical light transmission is more appropriate to characterise a covering material. This was demonstrated by Hemming et al. (2008) by testing two different films for which the perpendicular and hemispherical light transmission were measured both in the lab as in the covered greenhouse. The results of this test showed that the hemispherical light transmission correlates well with the average light transmission of a covering under practical conditions inside the greenhouse. Therefore it is concluded that the hemispherical light transmission is the most appropriate factor for characterising transmission of greenhouse covering materials.

## 5.2. Covering

A greenhouse consists of multiple systems that should be well integrated to function in the best way possible. The structural system consists out of the framing, the flooring and the covering. This part treats the most important aspects of the greenhouse covering.

The covering of greenhouses, generically called glazing, has an enormous influence on the crop production capability of the greenhouse system. The covering of the greenhouse drastically affects the amount of type of solar radiation of the plant canopy which result in direct and indirect effects. The plant growth is directly affected by the used glazing of the greenhouse. The micro-climatic factors inside the greenhouse, such as air humidity and carbon dioxide concentration, are indirectly influenced by the used kind of glazing.

### 5.2.1. Materials

There are three general types of coverings used for greenhouses, which are explained in the next section:

- Glass
- Rigid plastic panels
- Plastic films

#### Glass

Glass is a traditional covering material for greenhouses, because it is an attractive, very transparent and formal (in appearance) covering material. However, it is not the most economic choice, because it is relatively heavy (thickness varies from 2 to 6 mm (Ponce et al., 2014) ) which results in a more rigid supporting structure. Glass is quite inert, compared to plastics and can be used for many decades because it is resistant to radiation, air pollutant degradation and it maintains the initial radiation transmission. A dominant drawback of glass is its vulnerability to catastrophic losses caused by hail.

Glass is in the Netherlands and the North-Western region of Europe by far the most commonly used covering material (Hemming et al., 2004). Clear float glass with a thickness of 4 mm is usually used in horticulture greenhouse coverings. Other glass types used in greenhouse coverings are: toughened glass, white glass, double glass and hortiplus.

#### Rigid plastic panels

Plastics have revolutionized the greenhouse industry and many new greenhouses are covered with plastics. This caused the use of fibre glass to drop (Giacomelli and Roberts, 1993). Plastics are lightweight and are an economical choice. The mechanical and optical properties of plastics can be adapted to the wishes of the users. However, plastics have a limited lifetime due to degradation of the physical properties by exposure to UV radiation, pesticides and weathering.

Rigid plastic panels are used in two forms: single-walled and double-walled panels. Single-walled flat panels have a low stiffness and strength and a relatively large thickness has to be used to create sufficient stiffness. This results in uneconomical panels and thus flat panels aren't applied that often. The single-walled panels can be produced as corrugated or trapezoidal plates to increase the stiffness of the plate. These plates can be made from materials such as PMMA, PC, PVC and GRP. Double-walled plates are developed to realise an increased insulating value. Double-walled panels are made from the materials PMMA and PC. Interest in the use of double-walled plastic panels is currently increasing in the Netherlands in terms of energy saving, particularly for intensive field floriculture. The material PVC is in the past used, on a limited scale, for greenhouses, however this caused problems (damage) with hail load (Hemming et al., 2004).

### Plastic films

Plastic films are used in a wide variety of fields, climates and for various crops. Polyethylene (PE) is the most commonly used material for plastic greenhouse covering films, because of the many opportunities and non-toxic properties. The lifespan of these films is less than a year when no UV additives are applied. An advantage of the use of plastic films is the weight reduction and good optical properties. However, most of the plastic films are hydrophobic and this results in the condensation of water in the form of droplets on the surface of the film. This increases the light reflection and heat loss, which are unwanted effects.

A recent development is the introduction of a couple of high transparent plastic films such as EFTE, PVDF, TPU and PET. These films have good light transmissive properties, 90-95 % PAR, and a life span over ten years. The mechanical properties of these films are not the most optimal, for example TPU has a large strain and PVDF and PET are sensitive to tearing. However, these materials for plastic films are promising as they continue to be developed (Hemming et al., 2004).

## 5.2.2. Design Parameters

When designing a greenhouse, the design decisions for the greenhouse system should be based on the crop and its biological requirements. However, the selection of the covering is crucial for the realisation of an optimal controlled environment and thus the selected covering should help achieve the desired end product. Not only the strength, durability, consistency and safety of the material should be considered, but factors like the transmission of the solar radiation and energy conservation are important for the choice of the covering material. The last two factors will be explained into more detail, because they are very important in order to determine the quality of the greenhouse covering.

The solar radiation transmission of the glazing is the capability to transmit wavelengths that are useful to plants (400 to 700 nm). Solar energy can in general be transmitted, reflected or absorbed by the greenhouse covering. The transmitted portion (1 to 5 %) is needed for the plant growth, the remainder is absorbed and re-emitted as thermal radiation thereby heating the greenhouse air. The transmittance ($\tau$) is a physical property of the covering material, it is the ratio of the measured radiation intensity beneath the covering material ($I$) to that measured simultaneously above ($I_o$). The solar radiation consists of a diffuse and a direct component. Both components are important for the plant growth, but they can also both be influenced by the covering material. For example, plastic films increase the diffuse component while reducing the direct component. This influences the growing conditions inside the greenhouse. Giacomelli and Roberts (1993) present in their paper a method to compare greenhouse coverings based on the potential for plant growth and development. However, there is also the possibility to determine the light transmission by computer simulation or actual measurements.

The energy conservation is important for the heat retaining properties of the glazing during long nights and cloudy days. Therefore the energy should be conservated, which means that the energy input (solar radiation and/or heating devices) must balance the outflow (energy losses due to convection, radiation or infiltration).

## 5.2.3. Requirements

A selection of requirements for the greenhouse covering properties are stated by TNO in the research report of Janssen et al. (2006), a summary is shown in Table 5.1.

**Table 5.1:** Requirements for greenhouse covering design, adjusted from Janssen et al. (2006)

| | **Min. requirement** | **Desired** |
|---|---|---|
| PAR transmission direct | >90% | >94% |
| PAR transmission diffuse | >82% | >86% |
| U-value | <7.5 $W/m^2K$ | <7.5 $W/m^2K$ |
| Minimum life time | 15 years | >15 years |
| Technology Readiness Level (TRL) | pilotscale | industrial scale |

## 5.3. Supporting Structure

Greenhouse systems are in general low cost and should be easy to transport and assemble. However, each greenhouse is designed for its specific requirements such as location and type of crop that will be cultivated. This results in a wide variation of supporting structures that are used for greenhouses in the Netherlands. This section presents an overview of the most common aspects of the supporting structure in greenhouse designs.

### 5.3.1. Types of Structures

Two different type of greenhouses can be distinguished according to the Dutch design standards (Normcommittee 351 037 "Kasconstructies", 2012):

- Type A: Greenhouses where (part of) the covering system allows only limited frame displacements due to design loads. Therefore greenhouses with a rigid covering material, such as glass or hard plastics, are referred to as type A.
- Type B: Greenhouses where the covering system does not have restricted frame displacements due to design loads. Therefore greenhouses such as foil greenhouses, foil tunnels, shade halls, are generally indicated as type B.

The two types of supporting structures that are commonly used in the Netherlands for a type A greenhouse are: the Venlo system (Venlokas) and the Widespan system (Breedkap). Greenhouse systems that are less commonly used in the Netherlands are: arch systems (boogkassen), convertible greenhouses (cabrioletkassen), tunnel and foil greenhouses (tunnel- en foliekassen) and shadow halls (schaduwhallen). The two main types of greenhouse systems (Venlo and Widespan) are treated in the sections below.

#### Venlo System

The Venlo system is the most frequently used greenhouse system. This type of structure is built-up of glass with a galvanized steel and aluminium skeleton. For maintaining a good indoor climate the rule of thumb applies that the lower the crop height, the higher the greenhouse system. This is why Venlo systems are mainly used for the cultivation of vegetables (tomatoes, paprika and cucumber) and cut flowers.

A Venlo system has a typical bay width of 3.20 meters. However, in the last years Venlo systems with a different width are developed. Usually, two, three or four caps are supported by one horizontal support, hereby increasing the free space between the supporting legs to 8 or 12.8 meters. The distance between the columns in the direction parallel to the gutter is also increased in the last years from 3 to 4 or 5 meters. The height of the legs, the gutter height, has increased to 8 meters over the years. Figure 5.3 gives an example from the inside and Figure 5.4 shows a typical build up of a Venlo system greenhouse.

**Figure 5.3:** Example of a Venlo greenhouse system, image provided by Boal Systemen

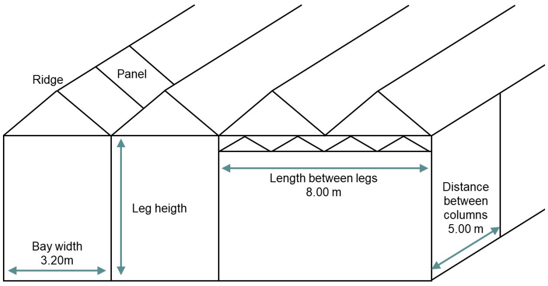



**Figure 5.4:** Typical build up of a Venlo system

#### Widespan System

The Widespan system has a built-up that is similar to that of a Venlo system. However, the advantage of a Widespan system is the efficient and economical work space, because less columns are needed. The large volume ensures a balanced climate in the greenhouse, compared to the Venlo system which is unsuitable for optimal energy utilization.

The span of the trusses is standardised to sized of 8, 9.6 and 12.8 meters. Other sizes are also possible, but are not commonly used. The gutter height is usually higher than 5.5 meters. Figure 5.5 gives an example from the inside and Figure 5.6 shows a comparison of a typical build up of a Widespan and Venlo greenhouse system.

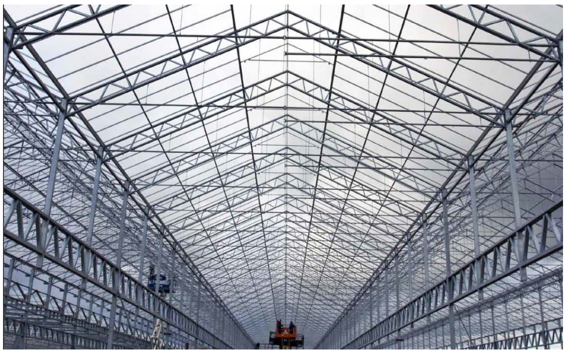


**Figure 5.5:** Example of a Widespan greenhouse system, image provided by Boal Systemen

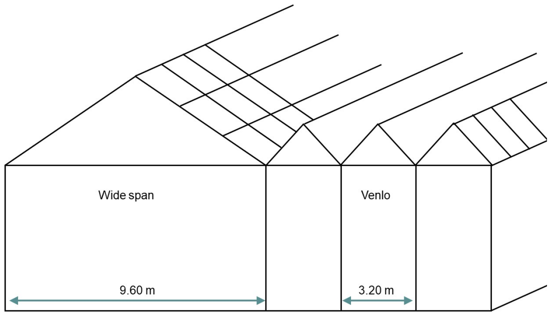



**Figure 5.6:** Comparison of the build up of a Widespan and Venlo greenhouse system

## 5.3.2. Materials

The greenhouse systems consist of various materials. The foundation is usually made of concrete, sometimes a piled foundation is needed when the bearing capacity of the soil is not sufficient. The horizontal trusses and diagonal supporting beams are generally made out of steel, while the greenhouse covering system is made of aluminium.

## 5.3.3. Components and Connections

The aluminium covering system consists of gutters (goot), roofbars (roede) and ridges (nokprofiel). Each glass (or plastic) panel is supported by one gutter, one ridge and two roofbar profiles. The ridges connect the two sloping parts of the roof. The rainwater is transported from the roof through the gutter. The roofbars ensures that the glass panels remain in place in the longitudinal direction of the greenhouse.

Typical aluminium profiles and connections for the ridges, gutters and roofbars for a Venlo system with glass panels of 4 mm thickness are shown in Appendix C.

## 5.3.4. Loads

A greenhouse is a complex system in which multiple disciplines need to be combined to create an as efficient system as possible. This results in the fact that several different loads from the different components of the greenhouse system should be taken into account for the design of the supporting structure.

The different loads that normally have to be taken into account are (ISSO Foundation, 2015):

- Permanent loads
- Permanently present installation loads
  - Crop load
  - Hanging cultivation gutters

  - Roof sprinklers
  - Double cultivation layers
  - Irrigation pipe load
  - Tensile forces by screening
  - Lighting
  - Crop wires
- Wind load
- Snow load
- Concentrated vertical loads
  - Load from fixed devices
  - Load by individuals
- Occasionally present system load
  - Service rail
  - Greenhouse roof cleaner / service cars
  - Transportation forces
- Thermal loads

Load combinations must be used for all loads that may occur at the same time, according to NEN3859 (Normcommittee 351 037 "Kasconstructies", 2012). However, loads that can not occur simultaneously, for example due to physical reasons, do not need to be assessed in combinations.

## 5.4. Insurance

Costs can add up very quickly when a greenhouse is damaged due to the large areas, brittle materials, crops and used climate control systems. This has resulted in the development of insurance companies that are specifically for the greenhouse industry. The research is mainly focussed on the structural possibilities of applying thin glass in greenhouse covering. However, the reduction of costs and risks are such an important factor in the greenhouse industry that it is necessary to understand the basic principles and thereby occurring problems and possibilities of greenhouse insurances. This section will firstly treat the general functioning of the greenhouse insurances. Hereafter, the influence of more extreme weather events is treated. Finally, the role of the insurance companies in the greenhouse industry is explained.

### 5.4.1. Functioning of Greenhouse Insurance

#### General

An insurance can be defined as a financial product sold by an insurance company to safeguard property against the risk of damage. A business insurance is designed to keep a business running, whatever happens in the future.

The general principle of an insurance is that regular payments are made, known as premiums, to the insurer by the insured party. A claim can be made when damage has occurred and the insurer will pay out the loss that is covered under the policy. When no claims are made the money that is paid by the premiums is pooled with the premiums of the other policyholders who have taken out an insurance with the same insurance company. The money that is paid by the insurer in case of a claim comes out of this pool of policyholders' premiums. Figure 5.7 shows the general principle of the functioning of an insurance.

Insurers use risk data to calculate the likelihood of the insured event against happening. The more likely the event is to occur, the higher the risk to the insurer and the higher the cost of the premium.

#### Greenhouse

For greenhouse insurances, a distinction is made between the greenhouse covering, the crop, the assets and the company building. The graduation research focusses on the greenhouse covering and therefore this insurance will be treated into more detail in this section.

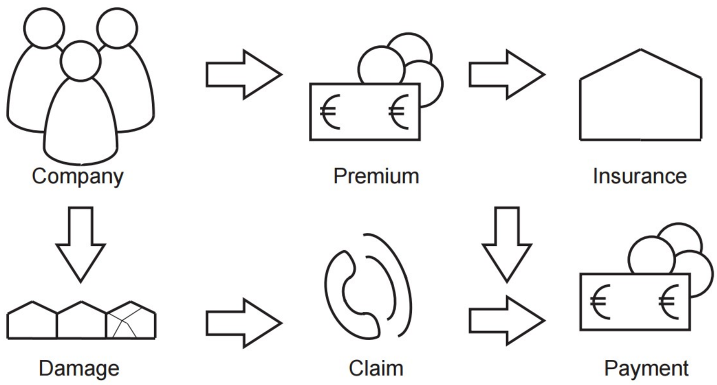



**Figure 5.7:** Visualisation of general principle of insurance functioning

The basic principle of the insurance of the greenhouse covering is that it is insured against external factors such as storm, hail and water (see Figure 5.8). The crop is thus standard insured for damage due to the damaging of the greenhouse covering by these external factors. However, an additional insurance is necessary for the crop to insure against damage by other factors.

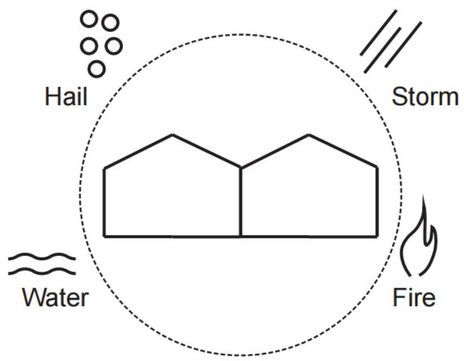



**Figure 5.8:** Factors insured for greenhouse coverings

The total premium for the greenhouse covering consists out of four main risks: fire, hail, storm and flooded gutters. A certain factor is assigned to each of these risks and together they make up the total premium. For each risk a certain amount of money is put into the pool, according to the factors and the number of claims that will be made. This pool serves as a back-up for the claims that must be paid each year. A visualisation of this process is shown in Figure 5.9.

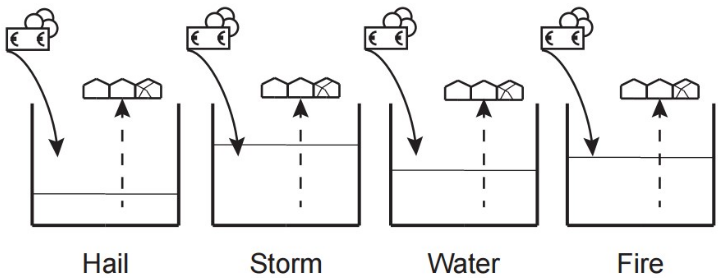



**Figure 5.9:** Visualisation of insurance pools

The average premium for a greenhouse with functional equipment such as screens and aeration installations is approximately 27.5 eurocents per $m^2$ (source: email contact on 28th of May with W. Snoeker, Interpolis). This is a rough average, because it covers all types of greenhouses, new and old etc. are included. For a modern greenhouse, the average premium increases because of the invested amount for the new structure of the greenhouse, but also because more equipment and installations are used which results in a higher representative value.

#### Risk Assessment

The insurers use risks to determine the desired premium for the greenhouse covering insurance. The premium for a greenhouse covering insurance depends on the value of the greenhouse due to the large variety in used materials, coatings, systems etc. The risk assessment of a greenhouse is based on the European standards (NEN norm) and focusses on the quality and strength of the material for the roof covering. For example, the properties of plastics decrease with the year and because of this the increase of fracture-sensitive behaviour has to be included in the determination of the premium.

Glass is the most commonly used greenhouse covering material in the Netherlands and the biggest part of the applied clear glass is annealed float glass. However, annealed glass has a low strength while tempered glass has increased strength and thus reduces the risk of damage. Therefore, the premium can be decreased when tempered glass is applied in a greenhouse covering. The purchase of tempered glass is more expensive than annealed glass, but the reduced premium can be beneficial for the horticultural company on the long-term. The insurer demands the use of tempered glass when diffuse coatings are applied, because of the higher costs of coated glass and an increased risk for the insurer when coated glass is damaged.

The decrease of the premium by the increase in strength and reduction of the risk of damage is interesting to keep in mind when developing new materials for greenhouse coverings.

### 5.4.2. Extreme Weather Events

As explained previously, risk data is used to calculate the likelihood of the insured events against happening. Important risk data for the greenhouse covering insurance is the data about the occurrence and impact of weather events such as storm, rain and hail. The likelihood of damage occurring by these weather events determines the height of the premium, so that all the losses by these events can be paid back by the insurers as fast as possible.

From 2014 onwards, a trend of more local storms and more heavy hail storms is noticeable. In 2015 Interpolis Agro paid about 20 million Euro for hail related damage, in 2016 this amount even increased to 140 million Euro after the summer hail storm in Someren (source: meeting with W. Snoeker, Interpolis).

The extreme hail events of the last years caused more damage than predicted. The consequence was that the amount of money in the hail pool, the money that is reserved from previous years, was not sufficient for the losses that had to be paid due to the increased hail damage. A temporary solution had to be sought and resulted in the fact that money from the storm pool was used to pay all the hail claims, see Figure 5.10. The problem of this temporary solution is that not only the temporary borrowed money from the storm pool must be paid back, but also the money from the hail pool should be supplemented. The trend of increased hail events ensures that the factor for the hail risk must be raised and therefore the total premium will also increase.

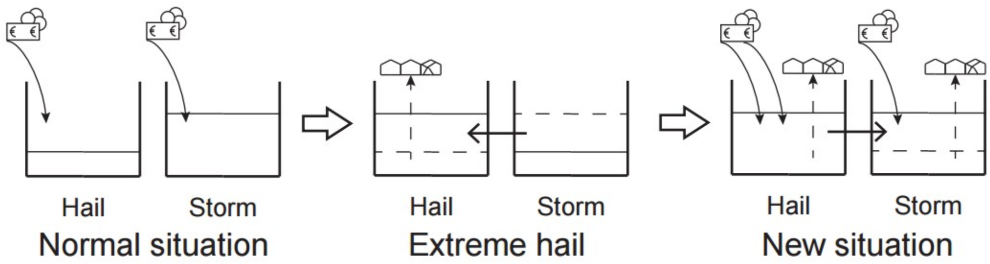



**Figure 5.10:** Visualisation of insurance for extreme weather events

### 5.4.3. Role of Horticultural Insurance Companies

The Dutch horticultural sector is well-known all over the world. This has also ensured that the Dutch horticultural companies are not only operating in the Netherlands, but all over the world. The cooperation between the horticultural companies is vital for the Dutch sector to remain a global leader. Therefore the role of the horticultural insurance companies is different than that from a regular insurance company. The insurance company does not only buy off the risk, but they also provide damage prevention tips and establish collaborations between different horticultural companies for creating risk reducing innovations such as fire resistant screen canvas. Innovation is necessary to maintain the leading position in the greenhouse sector. Therefore the Netherlands has set-up a fund, Stichting Hagelunie, that is used to assist innovative research for the greenhouse sector.

# PART III

Concept Study

# 6
# Scope Definition

Greenhouses are complex systems for which miscellaneous factors have to been taken into account to arrive at an optimal design and high yield. The choice is made to first clearly define the scope before continuing the rest of the research. This chapter treats firstly the boundary conditions of both the research and the greenhouse system. Hereafter, the parameters for the considered greenhouse system are stated. A division is made between parameters for geometry, positioning, supporting system and light. Lastly, the reference greenhouse unit which will be used for the rest of the research is presented.

## 6.1. Boundary Conditions

It is important to set boundary conditions for both the research itself and the system being tested in order to have the ability to control the direction and duration of the research. The individual boundary conditions for the research and the greenhouse system are presented in this section.

### 6.1.1. Research

A concept study is performed to explore the applicability of thin chemically strengthened aluminosilicate glass in greenhouse coverings. No extremely detailed experiments and/or modelling is carried out, so that the concept study will maintain its general character. Recommendations will be made for the necessary into depth research that need to be performed for further and detailed investigation.

The research is limited to four main research areas: building physics (Chapter 7), structural properties (Chapter 8), structural design (Chapter 9) and economics (Chapter 10). This subdivision is made in order to create a focussed research on both building physics and structural properties for the applicability of thin chemically strengthened aluminosilicate glass.

### 6.1.2. Greenhouse System

The greenhouse cover is considered to be infinitely large, which means an infinitely repeating unit in the horizontal plane, so that no edge effects occur. In this research the system boundary is defined above the crop and below the greenhouse roof supporting system.

The used greenhouse system is a Venlo system with inclined gutter, ridge and rods. It is assumed that the remaining structural parts are located below the greenhouse covering material and that they do not influence the type of greenhouse covering material, slope or orientation. A reference greenhouse will be used to compare the results of the designed system in which thin chemically strengthened aluminosilicate glass will be used. The reference greenhouse is treated later in this chapter.

## 6.2. Parameters

A greenhouse design consists of many different components, which are usually adapted to the specific requirements of the situation. However, for this research the choice is made to specify certain parameters for the greenhouse system on beforehand. The choice for the parameters is based on the available literature.

### 6.2.1. Positioning

**Greenhouse system** TNO performed research for the differences in light transmittance of a Venlo and arch roof for diffuse light (Janssen et al., 2006). The results show that the light transmission properties of a Venlo and arch roof are comparable without the roof system. However, the Venlo roof has a better light transmittance performance when the roof structure is taken into account. The differences between the light transmittance of an Venlo and arch roof are relatively small. There is chosen for the research to first look into the possibilities of applying thin glass in a Venlo type of greenhouse, but the use of an arch roof can be interesting to investigate when intermediate results of the research show that it is not possible to use thin glass in a Venlo system.

**Orientation** Research from S. Hemming and TNO shows that a North-South ridge orientation will ensure the highest light transmission the whole year round, while an East-West orientation will perform better in the winter months (Janssen et al., 2006; Hemming et al., 2004).
The goal of this research is to achieve the best performance of the greenhouse covering all year round and therefore the choice is made to use a North-South ridge orientation.

**Inclination** Research by TNO shows that a roof inclination of 26 degrees has the general highest transmission all year round (Janssen et al., 2006). Due to the goal of achieving the best performance all year round this value is used for the research.

**Geographical location** The research is limited to the Netherlands, because of the available light research results for this location and the application of glass in greenhouses in the Netherlands.

### 6.2.2. Geometry

**Thickness** The available sample thicknesses of the chemically strengthened Leoflex glass are 0.55, 1.1 and 2 mm, while chemically strengthened Leoflex glass with a thickness of 0.55 and 0.85 mm is used by the WUR for the light transmittance research. This results in the choice for a thickness of 0.55 mm for the research to the possibilities of applying thin chemically strengthened aluminosilicate glass in greenhouse coverings.

**Shape** The research is limited to rectangular shaped panels, because this is the most convenient shape that is used in greenhouse systems and therefore other shapes are excluded from this research.

**Dimensions design** One of the goals of the research is to investigate in which way thin glass can be applied in a greenhouse covering. Most of the greenhouses are designed with standardised dimensions to limit the costs of the design of the supporting system. There is chosen to use the most applied standardized dimensions for the research to thin glass in a greenhouse covering.
The standardised dimension at this moment are, according to Boal:

- Bay width: 4,000 mm

- Section size: 5,000 mm
- 4 panels per section size
- Length rods: 2,180 mm
- Width panel: 1,245 mm
- Length glass panel: 2,175mm

**Dimensions experiment** The samples of the 0.55 mm Leoflex glass are already present at the start of the research. These samples will be used for (scale) experiments and thus the dimensions of the experiments are fixed to 710 x 360 mm.

### 6.2.3. Supporting System

**Material** The research is limited to the material aluminium for the supporting system. This is chosen because of the collaboration possibilities with companies such as Boal for the detailing of the connections and supports.

**Ventilation** The research is limited to a closed greenhouse covering system and therefore the ventilation openings and opening mechanisms are not taken into account.

**Connections** The research is limited to the connections of the glass to the gutter, ridge and rods.

**Design life** The assumed greenhouse type is A because of the hard covering material (Normcommittee 351 037 "Kasconstructies", 2012). The design life of the system is assumed to be 15 years and therefore the type of greenhouse is an A15 type.

### 6.2.4. Light

**Artificial/natural** The research is limited to the natural light and therefore artificial light is excluded.

**Coatings** The research is limited to clear thin chemically strengthened aluminosilicate Leoflex glass and therefore the influence of coatings on the light transmittance of the covering material is not taken into account.

**Light transmittance** The research is limited to the hemispherical and perpendicular light transmittance as explained in Chapter 5, the day length and spectral distribution in relation to red and blue receptors in the plants are excluded.

**Condensation** The influence of condensation on the light transmittance is not taken into account for this research.

**Season** The research is performed for the best results all year round and therefore the special requirements for summer or winter are not taken into account.

**Supporting system** The research on the influence of the supporting system is limited to the light interception and therefore the reflection, absorption etc. of the supporting system are not taken into account.

## 6.3. Reference Greenhouse Unit

The reference greenhouse design consists out of a small unit of 4 by 5 meters that is infinitely repeated in the horizontal plane, so that no edge effects occur. The design of the reference greenhouse unit is based on the commonly used dimensions in the current (Venlo) greenhouse systems as mentioned by Boal, see Table 6.1.

**Table 6.1:** Dimensions and set parameters of reference greenhouse unit

| **Glass** | | |
|---|---|---|
| Glass type | Float glass | - |
| Coating | Clear glass | - |
| Width glass | 1,245 (4 per bay) | mm |
| Length glass | 2,175 | mm |
| Thickness glass | 4 | mm |
| Hemispherical light transmittance | 82 | % |
| | | |
| **Supporting system** | | |
| Material supporting system | Aluminium | - |
| Greenhouse system | Venlo | |
| Inclination | 26 | ° |
| Orientation | North-south | - |
| Geographical location | Netherlands | - |
| Bay width | 4,000 | mm |
| Section size | 5,000 | mm |
| Height columns/legs | 6,000 | mm |
| H.t.h. distance rods | 1,250 (4 per bay) | mm |
| Length rods | 2,180 | mm |
| Rod dimensions | HxW = 45x23<br>Type: B50701 | mm |
| Gutter dimensions | HxW = 144x119<br>Type: VWL | mm |
| Ridge dimensions | HxW = 30x37<br>Type:B50343 | mm |

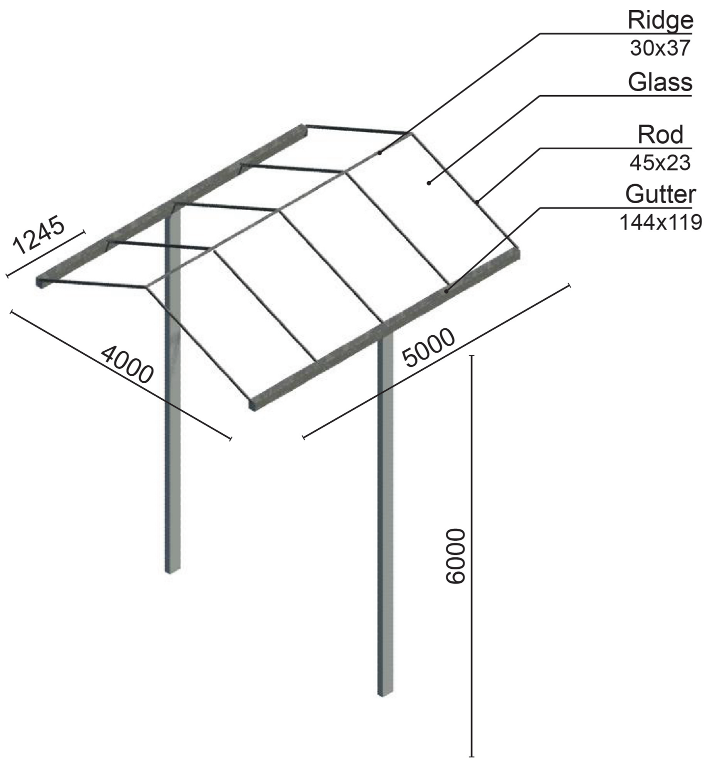



**Figure 6.1:** Visualisation of reference system

# 7

# Building Physics

Two important factors that determine the quality of a greenhouse design are the light transmittance and the thermal properties of the greenhouse covering. These two topics are treated in this chapter. Firstly, the light transmittance properties of thin chemically strengthened aluminosilicate glass are treated. The experiments as performed by the WUR research team and according measurement set-up and procedures are presented. Hereafter, the results relevant for this research are given. Secondly, the thermal properties for the application of one or multiple thin glass layers are determined. Lastly, the conclusions are presented for the light transmittance and thermal transmittance properties of thin glass.[1]

## 7.1. Light Transmittance

Research is conducted to the light transmission of several covering materials for greenhouses at the Wageningen University & Research (WUR). A collaboration is started with Dr. S. Hemming, head of research team Greenhouse Technology at the WUR. The Wageningen UR LightLab is a unique facility with the most modern measurement equipment for optical properties of greenhouse materials. The Greenhouse research team at the WUR is specialised in light research for greenhouses. This is why there is chosen for a collaboration and to use their data for the light transmission of glass in a greenhouse covering.

### 7.1.1. Measurement System

Until recently, the only norm available for measurement of the light transmission of greenhouse glass was the Dutch norm NEN 2675. However, this norm is no longer appropriate for the determination of the optical performance of greenhouse covering materials other than standard float glass. The introduction of new materials different than float glass resulted in the development of a new measuring protocol by TNO and the WUR. In line with this protocol, the WUR has developed a new device (Transvision) for measurement of the angular and hemispherical transmission of transparent (greenhouse covering) materials as well as the haze (Swinkels, 2012).

The operation of this measurement device and corresponding protocol are shortly explained in the next sections.

[1] The light transmittance data presented in the chapter are interim progress results as obtained by the WUR. These results have been shared by Dr. S. Hemming. Only the numbers relevant for this graduation research are presented in this chapter. However, the research for the optical qualities of thin glass has not yet been completed. The analysis can be completed when all tests have been carried out and the results are known by the WUR research team. Only then a complete picture can be painted of the optical properties of the thin glass with the associated advantages and disadvantages for application in greenhouse coverings.

### Integrating Sphere

A large integrating sphere at WUR LightLab is used to measure the optical properties of all glasses (Hemming et al., 2014). An integrating sphere, also known as an Ulbricht sphere, is an optical component that is used for the measurement of the light transmittance properties of materials. The integrating sphere consists of a hollow spherical cavity. The interior is covered with a diffuse white reflective coating (for instance Spectralon) and has small holes for entrance and exit ports. Light rays incident on any point on the inner surface are distributed equally to all other points by multiple scattering reflections. The size of the sphere largely determines the accuracy of the measurement. The light intensity decreases strongly with the diameter and this complicates measurement.

A Xenon light source is attached on a movable arm so that the angle of incident light can be changed on the sample that is mounted on the opening of the sphere, see Figure 7.1.

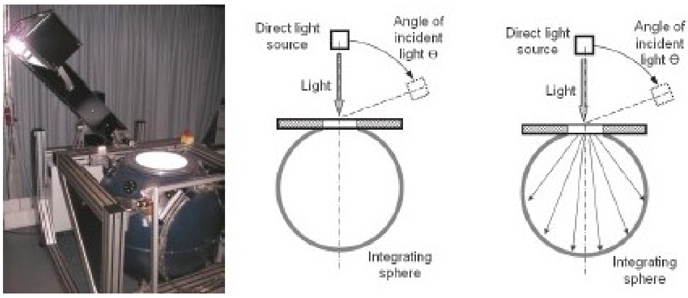



**Figure 7.1:** Schematic overview measurement system for hemispherical and perpendicular light transmittance (Hemming et al., 2014)

The integrating sphere is equipped with a diode array photo spectrometer. This spectrometer records the entire spectrum at once, instead of one wavelength at a time. A typical diode array photo spectrometer responds to both visible and ultra violet radiation. The spectral light transmission ($\tau_\lambda$) can be measured for wavelengths of 300nm<$\lambda$<1,100nm in steps of 1 nm.

### Method

Fully automatic measurements are carried out with and without samples and all data is stored automatically on a computer. Standard materials with known properties are used for calibration purposes. Repetitive measurements allow measurement results with a standard deviation of $\sigma$<0.2% for perpendicular light transmission and $\sigma$<0.5% for hemispherical light transmission (Hemming et al., 2014). The properties that are determined are: perpendicular PAR transmission ($\tau_p$), angular light transmission under different angles ($\tau_\alpha$), hemispherical light transmission ($\tau_h$) and haze ($\eta$). For perpendicular light transmission the angle of incident light is zero degrees, while the angle of incident is changed between 0 and 90 degrees for the hemispherical light transmission. The reflection is measured after irradiating the sample from inside the sphere, while the haze is measured inside the sphere.

Two different standards (protocols) are used:

- NEN2675 is used for the determination of the perpendicular PAR transmittance
- TNO-WUR is used for the determination of the hemispherical light transmission and the haze

The protocol consists of the following steps (Janssen et al., 2006):

1. Measurement of the angle-dependent transmission at a sufficient number of angles of incidence (minimal 0, 45, 60 and 75 degrees), for anisotropic materials if necessary along both axes;
2. Fitting procedure with spreadsheet for the determination of the coefficients (possibly pre-fitting the different directions);
3. Calculating the angle-dependent transmission by using the fitting coefficients;
4. Calculating the diffuse transmittance.

### 7.1.2. Results

The results of the light transmission measurements for thin glass that are performed by the WUR are not yet presented in a paper. However, the preliminary results are made available for use in this research by Dr. S. Hemming.

#### Thin Glass

The results of the light transmittance tests on uncoated regular and thin glass performed by the WUR are shown in Table 7.1.

**Table 7.1:** Light transmission results uncoated regular glass and thin glass as provided by the WUR team

| **WUR code** | | AGC17A | AGC17I | HK 16A | HK 16B | HK 16C |
|---|---|---|---|---|---|---|
| **Glass description** | Single Normal | Single Extra Clear | Double Extra Clear | Single Leoflex | Double Leoflex | Triple Leoflex |
| **Thickness 1 layer** | 4 mm | 4 mm | 4 mm | 0.55 mm | 0.55 mm | 0.55 mm |
| **Total thickness** | 4 mm | 4 mm | 8 mm | 0.55 mm | 1.10 mm | 1.65 mm |
| **Hemispherical light transmittance** | 82% | 83.9% | 74.7% | 84.0% | 75.3% | 68.9% |
| **Perpendicular light transmittance** | 89.5 % | 91.5% | 84.2% | 91.6% | 84.5% | 78.3% |

#### Coated Glass

Diffuse light is favourable for crop production as explained previously in Chapter 5. Coatings can be used on glass to decrease the reflections and to ensure the transmittance of diffuse light into the greenhouse. The use of coatings can increase the production up to 10% and thus an interesting subject for which a lot of research is performed. In the scope definition, Chapter 6, is stated that the influence of coatings is not taken into account for the research that is presented in this report. However, this section gives a brief overview of the light-transmitting properties of coated glass for a complete overview. The results of the light transmittance tests on coated glass performed by the WUR are shown in Table 7.2.

**Table 7.2:** Results light transmittance of coated float glass as provided by the WUR team

| **Glass code** | AGC17C | AGC17F | AGC17H | AGC17G |
|---|---|---|---|---|
| **Glass description** | Single Extra Clear | Single Extra Clear | Double Extra Clear | Double Extra Clear |
| **AR coating** | 1 x AR | 2 x AR | 2 x AR | 4 x AR |
| **Total thickness** | 4 mm | 4 mm | 8 mm | 8 mm |
| **Hemispherical light transmittance** | 86.8% | 90.8% | 78.9% | 85.5% |
| **Perpendicular light transmittance** | 94.4% | 98.0% | 89.4% | 96.0% |

The light transmittance properties of thin chemically strengthened aluminosilicate glass are not yet tested by the WUR. However, calculations are performed for a prediction of the light transmittance properties of thin glass (Leoflex). The results of the light transmittance calculations performed by the WUR are shown in Table 7.3.

**Table 7.3:** Results expected light transmittance of coated thin glass as calculated by the WUR team

| **Glass code** | HK16A | HK16B | HK16C | HK16D |
|---|---|---|---|---|
| **Glass description** | Single Leoflex | Double Leoflex | Triple Leoflex | Quadruple Leoflex |
| **AR coating** | 2 x AR | 4 x AR | 6 x AR | 8 x AR |
| **Total thickness** | 0.55 mm | 1.10 mm | 1.65 mm | 2.20 mm |
| **Hemispherical light transmittance** | 91.1% | 86.1% | 82.1% | 78.5% |
| **Perpendicular light transmittance** | 98.0% | 96.3% | 94.3% | 92.6% |

### 7.1.3. Clarification Differences

The previously mentioned results show a small difference of approximately 2% between the light transmittance of the regular float glass and thin glass. The transmittance of light is depending on the absorption and reflection of the incoming light, as shown in Figure 7.2.

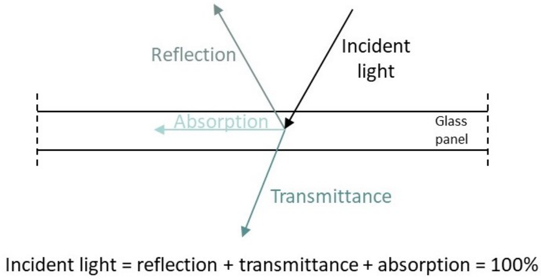



**Figure 7.2:** Illustration of light transmittance glass panel

For the WUR experiment, the incoming light and transmittance are known. However, the absorption and reflection are unknown. The reflection of the front side of a glass panel for perpendicular light can be calculated by using the Fresnel equation shown in Equation 7.1.

$$R = \frac{(n_{air} - n_{glass})^2}{(n_{air} + n_{glass})^2} \tag{7.1}$$

In which $n_{air}$ is the refraction index for air (1.0) and $n_{glass}$ is the refraction index for glass (1.52 for regular float glass and 1.51 for thin Leoflex glass).

However, the light is not only reflected on the front surface but also on the back. The total reflection of a glass panel can be calculated by Equation 7.2.

$$R_{tot} = 2R/(1+R) \tag{7.2}$$

The total reflection for regular float glass ($R_{tot,float}$) and thin glass ($R_{tot,thin}$) is thus:

$$R_{tot,float} = 8.2\%$$
$$R_{tot,thin} = 7.9\%$$

The incoming light, transmittance and reflection are known and thus it is also possible to calculate the absorption. The calculation results in a difference between the absorption and reflection of regular float glass and thin glass. A visualisation of the perpendicular light transmittance of regular float glass an thin glass is presented in Figure 7.3.

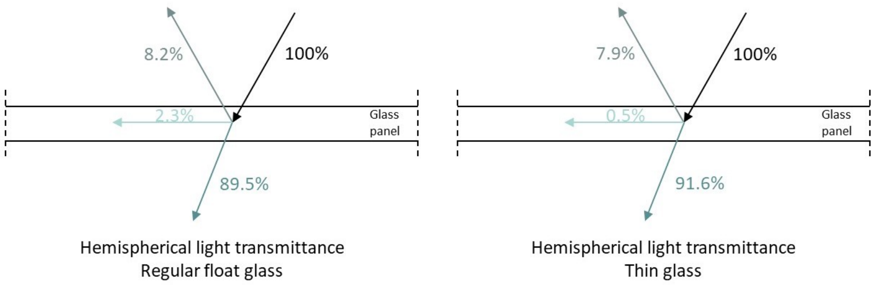



**Figure 7.3:** Visualisation of hemispherical light transmittance regular float glass and thin glass panel

A difference between the absorption and reflection of regular float glass and thin glass can be distinguished, which results in the higher light transmittance for thin glass. The difference in reflection can be explained by the difference in refraction index for float glass and thin glass (Leoflex). The difference in absorption can be explained by the difference in thickness. However, the absorption of glass is smaller than 2-3% and therefore the change in hemispherical light transmittance for thinner glass is also relatively small.

## 7.2. Thermal Transmittance

An important requirement for a greenhouse is to provide protection for the crop from variable weather conditions. For certain crops a constant temperature is required and insulating glass units can be used for maintaining a constant temperature with a low energy use. The light transmittance research at the WUR is performed for different configurations of single and multiple layers of thin glass, because of the possible application of thin glass in insulating glass units (IGU's). Therefore, the choice is made to perform a short study on the thermal transmittance properties of thin chemically strengthened aluminosilicate glass in different configurations.

### 7.2.1. Theory

The thermal transmittance of a structure is the rate of transfer of heat through this structure, divided by the difference in temperature across the structure. It is often referred to as the U-value and the units of measurements are $W/m^2K$. A low U-value stands for a good insulated structure, while a poorly insulated structure can be recognized by a high U-value.

The NEN-EN 673 ("Vlakglas", 2011) is generally used for the determination of the U-values for glass in buildings. The U-value can be calculated by Equation 7.3.

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i} \tag{7.3}$$

In which $h_e$ is the external heat transfer coefficient in $W/m^2K$, $h_i$ is the internal heat transfer coefficient in $W/m^2K$ and $h_t$ is the total conductance of the glazing in $W/m^2K$. These coefficients can be determined by using NEN-EN 673.

### 7.2.2. U-values

The U-values are calculated according to the NEN-EN 673 for different regular float glass (t=4 mm) and thin glass (t=0.55 mm) configurations. The U-value for a single glass plate and double glazing unit placed under an angles of 26° are calculated. The cavity of the double glazing unit varies from 6 to 20 mm. Two different gas fillings of the cavity are considered: air and argon. The resulting U-values are presented in Table 7.4.

**Table 7.4:** U-values for regular float glass and thin glass

| | Air filled cavity | | Argon filled cavity | |
|---|---|---|---|---|
| **Cavity** $[mm]$ | **Regular Float Glass** $[W/m^2K]$ | **Thin Glass** $[W/m^2K]$ | **Regular Float Glass** $[W/m^2K]$ | **Thin Glass** $[W/m^2K]$ |
| Single layer | 5.8 | 5.9 | 5.8 | 5.9 |
| 6 | 3.1 | 3.1 | 2.8 | 2.9 |
| 8 | 3.1 | 3.1 | 2.8 | 2.9 |
| 12 | 3.0 | 3.1 | 2.8 | 2.9 |
| 16 | 3.0 | 3.1 | 2.8 | 2.9 |
| 20 | 3.0 | 3.1 | 2.8 | 2.8 |

## 7.3. Conclusion

#### Light Transmittance

The performance of glasses for greenhouse coverings can be judged by the hemispherical light transmission and haze, as explained previously in Chapter 5.

The most simple glass that can be used in greenhouse coverings is uncoated clear glass. At this moment the most used glass panels for greenhouses are annealed or tempered soda lime float glass with a thickness of 4 mm. A hemispherical light transmittance of 82-83% is assumed for this kind of glass by the WUR team (Dr. S. Hemming, personal communication, 10 February 2017) and is taken as reference for further research.

The results show a hemispherical light transmission of 84.0% for uncoated clear thin glass (Leoflex t=0.55 mm) and 82% for uncoated regular float glass. The general rule-of-thumb *"1% less light in a greenhouse, is 1% less production or yield without the distinction between different crops or crop groups"* is generally used in the greenhouse industry (Hemming et al., 2004). Therefore it is stated that the hemispherical light transmittance of new glass covering material may therefore not be less than the presented 82%.

The combination of the experimental light transmission results and the general rule-of-thumb results in the following conclusions:

- The hemispherical light transmission of uncoated thin glass is higher than the limit of 82% and therefore it can be stated that thin glass may be used as greenhouse covering material regarding the light transmittance.
- The application of uncoated thin glass, compared to uncoated float glass, results in an increased hemispherical light transmission of 2% and subsequently an increased yield of 2%.
- The application of a diffuse coating for thin glasses, compared to the expected coated thin glass results in an increased hemispherical light transmission of 7-8%.
- It is not yet possible to draw conclusions for the increased hemispherical light transmittance for coated thin glass compared to coated float glass, because no experiments are yet performed for coated thin glass. Based on the calculations it can be expected that coated thin glass will result in an increased hemispherical light transmittance when compared to float glass. However, more experiments have to be performed on thin coated glass to draw detailed conclusions on the effect of coating thin glass compared to float glass.

### Thermal Transmittance

The calculated U-values show that the insulating properties for thin glass panels are comparable to regular float glass panels. The U-values for thin glass panels are slightly higher, which mean that the insulating properties are slightly worse than that of regular float glass panels. Filling the cavity with Argon results in better insulating glass units, this is as expected. Making a triple or even quadruple glazing will result in even better insulating properties, but the light transmittance will decrease much.

The short study on the U-values results in the following conclusions:

- The thin glass configurations have higher U-values than the regular float glass panels. However, the difference is very small and therefore it can be concluded that the insulating properties of thin glass in insulated glass units is comparable to the insulating properties of insulating glass units of regular float glass.
- Double glazing has a lower U-value and therefore better insulating properties than a single glass panel.
- Filling the cavity with Argon results in a lower U-value and therefore better insulating properties than filling with air.

# 8

# Structural Properties

This chapter treats the structural properties of thin chemically strengthened aluminosilicate glass relevant for the research. Firstly, the strength of glass in relation to the brittle behaviour and flaws is elaborated. Hereafter, the safety for a (structural) glass design is treated. Then the characteristic values for the bending tensile strength are given. Lastly, recommended methods for detailed determination of the structural properties such as bending and impact strength are discussed for application in future research.

## 8.1. Strength

Glass has a poor structural reputation, because it has brittle failure and breaks or shatters without a previous warning such as the yielding behaviour of steel. However, glass has a strong covalent molecular bonding between the silica and oxygen atoms and therefore the theoretical strength might even exceed 14,000 MPa (Pepi, 2002). In design practice, this strength is never used and the theoretical value for the strength of a sheet of glass is reduced due to surface flaws, notches and cracks generated during manufacturing and handling processes (Veer et al., 2010).

### 8.1.1. General

Glass is an amorphous material and has a very high theoretical strength due to the covalent bonding between the silica and oxygen atoms. The only “defect” in such a material is the interstitial molecular spacing on nanometre level. However, Griffith (1920) noted that the manufacturing process results in much larger defects on the micron level. Griffith was the first to hypothesize that there are microscopic cracks in every material, that these cracks are larger than the inter-atomic distance and that these cracks lower the overall strength of the material. His research showed by experimental results that these effects indeed determine the strength of glass.

The strength of glass is also changed by the presence of larger surface flaws. These can be the origin of cracks when put under stress, since the glass may be unable to accommodate the originated local stress concentrations. The presence of major flaws at the surface or the edges of the glass can generate local stress concentrations when the glass is put under strain, which may lead to crack formation. However, it is hard to predict whether an individual flaw is likely to develop into a crack. Likely starting points for crack propagation are these small defects in the glass as they cause unacceptable stress concentrations. The presence of large flaws is one reason why the edge region of a piece of glass is usually weaker than the surface, where it is much more prone to damage from accidental contact.

### 8.1.2. Flaws

Three potential modes of flaw failures can be distinguished according to Pepi (2002), mode I, mode II and mode III, as shown in Figure 8.1. The first is an opening mode, while the latter two are shear modes. The two shear modes (mode II and III) are rare and therefore only mode I will be treated because it is the most important and dominant failure mode.

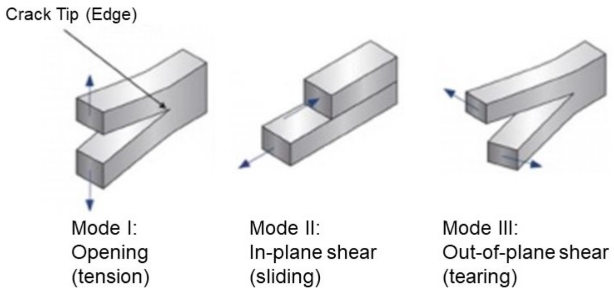



**Figure 8.1:** Visualisation of three possible crack modes, image adjusted from Pepi (2002)

Mode I is an opening mode, as told previously, and not a closing mode. This means that flaws will fail at a critical depth under external tension and not in compression. The compressive strength of glass exceeds the flaw reduced tensile strength. The strength in a sheet of glass loaded under compression is usually limited by buckling and therefore failure due to an exceeded compressive strength almost never occurs.

The flaws are mostly results of the production method and the handling of the glass afterwards. However, new defects can arise after installation of the glass due to weathering and human interaction. Without the post processing the chance on the presence of defects is increased, as treated in Chapter 4. However, post processing such as grinding simply reduces the depth of flaws, but does not completely remove them.

The size and shape of defects influence the strength. A larger flaw size leads automatically to a lower strength of the glass. The presence of flaws cannot be totally avoided and thus a certain level of flaw-depth must be accepted. This leads to a rather low design strength of glass compared to the theoretical possibilities. The shape and size of defects are hard to measure, especially the depth of a defect. Therefore, the strength of a glass panel is usually obtained by performing (bending) tests. Because the presence of a defect is based on statistics, the size of the sheet itself is also relevant. A larger sheet has an increased chance of containing a major flaw and therefore, on average, it can be stated that a bigger panel has a lower strength (Aurik, 2017).

## 8.2. Safety

When designing structures it is important that the safety is accounted for. Safety is even more important when a design includes glass, because of the fact that it is a brittle material and the presence of a large spread in strength properties.

### 8.2.1. General

The design strength of glass is lower than the theoretical strength due to the presence of surface and edge flaws, as explained in the previous section. The values for the characteristic strength for annealed, heat-strengthened and fully tempered glass are mentioned in the Dutch national norm for glass design, NEN 2608. However, it can be discussed whether the approach used to obtain the values is valid. The ring on ring method that is used, stresses the glass surface which is of higher quality than the edges. An alternative testing method is the bending test. These tests have the advantage that they are easy to perform, relatively cheap and stresses the edges of the glass instead of the surface. However, significant differences are noticed in the results of bending tests between lying or standing test configurations (Veer et al., 2009).

### 8.2.2. Applicability Dutch Standards

The regulations from the NEN 2608 norm are considered to be inapplicable for chemically strengthened aluminosilicate glass. Firstly, because the strength of chemically treated glass is higher and therefore panels can handle higher stresses. Secondly, because questions can be raised regarding the serviceability limit state of chemically treated thin panels. The small thickness of the glass in combination with the high bending strength makes chemically treated aluminosilicate glass very flexible. A flexible structure isn't necessarily unsafe, but the NEN 2608 has set-up restrictions for the deflections because of the fear factor of users when a panel is deflecting. However, it is questionable if these values also need to be applied when chemically strengthened aluminosilicate glass is used, because these regulations do not allow to use the benefit of the flexibility of thin glass.

### 8.2.3. Characteristic Strength

The characteristic strength of a material is defined as the strength of the material below which not more than 5% of the test results is expected to fall. For design purposes, this strength value is reduced by using a factor of safety for the material, whose value is depending on the used design philosophy. The design strength of a material can therefore be calculated by:

$$\text{Design load} = \frac{Characteristic\,load}{Material\,safety\,factor}$$

The strength of a material is usually determined by conducting tests. It can be expected that it is possible to determine the average strength and a standard deviation after the performance of a significant number of tests on glass, in order to determine the characteristic strength of the material. However, the strength of glass is not normally distributed because it is not merely a material property, but is dependent of flaws, size etc. Veer et al. (2007) researched the influence of the different post-processing treatments on the statistical distribution of the strength properties. The test results showed that the strength of the glass is highly dependent on the processing treatment. Figure 8.2 shows the results obtained from bending tests on glass panels. A value of 20 MPa can be retrieved from this plot for the characteristic bending tensile strength of annealed soda-lime glass. The value of 20 MPa corresponds to a failure probability of $10^{-4}$.

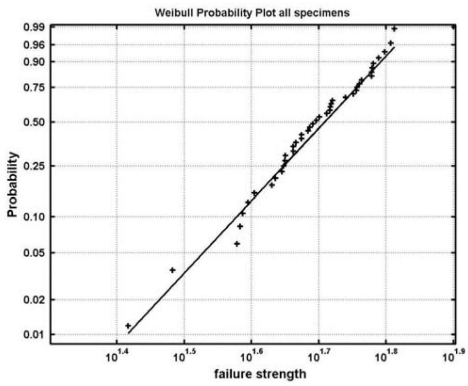



**Figure 8.2:** Weibull plot of bending tensile strength (Veer et al., 2007)

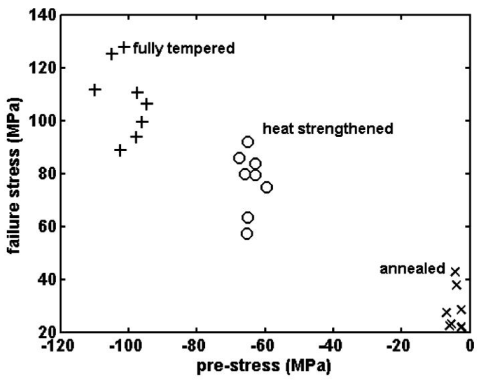



**Figure 8.3:** Relation between pre-stress and failure stress (Veer et al., 2009)

As stated previously, the characteristic values for the strength of glass presented in the NEN 2608 are arbitrary. Veer et al. (2009) researched the validity of the values by providing an independent set of values for the characteristic strength. The results of these tests are presented in Figure 8.3. It is still debatable if a certain guaranteed minimum can be defined, but the values from this research will be used for the rest of the research presented in this report. The used values are shown in Table 8.1.

The strength properties for the Leoflex glass, as provided by AGC, are shown in Appendix A. For a thickness of 0.55 mm it is stated by AGC that the compressive marginal stress for Leoflex glass is 260 MPa. However, no spread or additional information about the retrieval of this value is available and the values of the ultimate bending strength can vary between different manufacturers due to the lack of regulations. The values presented by AGC are usually lower than the values that are achieved by the first tests at Delft University of Technology. Therefore the choice is made to use the strength of 260 MPa provided by AGC for the characteristic bending tensile strength of thin chemically strengthened aluminosilicate glass.

A further study on the strength of thin glass was not possible within the scope of this research, however the tensile strength of thin glass is researched at the moment by R. Ottens at Delft University of Technology.

**Table 8.1:** Characteristic values used for research

| | DOL | Compressive Strength [MPa] | Bending Tensile Strength [MPa] |
|---|---|---|---|
| Annealed | 20% of thickness | 200 | 20 |
| Heat Strengthened | 20% of thickness | 200 | 40 |
| Fully Tempered | 20% of thickness | 200 | 80 |
| Chemically Strengthened (Leoflex) | 0.015 - 0.04 mm | 550 - 850 | 260[1] |

### 8.2.4. Post-Breakage Behaviour

Glass is a brittle material and does not possess any inherent ductility. This means that a glass element breaks suddenly without a warning and disintegrates after failure. For a safe glass design it is therefore important to look at the post-breakage behaviour of the element.

In most structural glass designs the post-breakage safety of the glass elements is improved by lamination of multiple glass panels with a PVB or SentryGlass interlayer. The interlayer ensures that the glass pieces of the broken panel are sticking to the interlayer and the intact panel, hereby preventing the falling down of the broken glass pieces. However, the interlayer materials block UV light which is important for the crop growth and therefore laminated panels are undesirable in greenhouses.

The breakage behaviour for regular float glass panels is different for the various pre-stressing methods, as shown in Figure 8.4:

- Annealed glass: has a low strength, but breaks in big pieces. The glass element does not collapse completely when damaged, but the damaged pieces can fall down. The broken pieces are sharp and dangerous when they fall down.
- Heat strengthened glass: has a higher strength and breaks in slightly smaller pieces than the annealed glass. However, these pieces are still sharp and dangerous when they fall down.
- Tempered glass: is four times stronger than annealed glass and breaks in tiny pieces. The pieces have no sharp edges, but when the element is damaged it collapses completely.

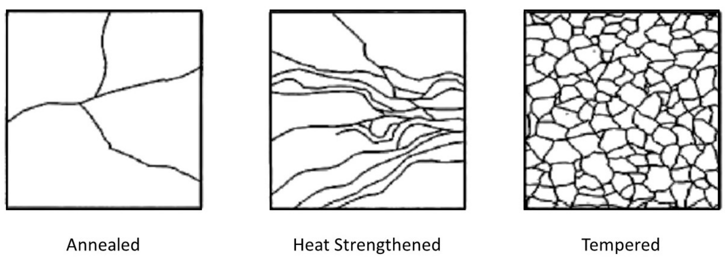



**Figure 8.4:** Breakage pattern of various pre-stressing methods of glass

The breakage behaviour of thin chemically strengthened aluminosilicate glass panels is not yet fully studied. The general expectation is that chemical strengthened glass has a similar breaking pattern as annealed glass due to the low tensile stresses in the core. During the research a chemically strengthened thin glass panels was

[1] Compressive marginal stress according to Leoflex data sheet (Appendix A)

damaged and a breakage pattern similar to annealed glass could be recognized. However, recently performed research to the bending strength of chemically strengthened thin glass showed different results. During this research the glass panel shattered comparable to tempered glass when a large compressive force was applied for the bending tests. The breakage behaviour of chemically strengthened glass is thus not yet clearly determined. It is therefore important to keep this into mind, when designing large chemically strengthened thin glass panels for greenhouse coverings. At this moment no specific requirements are available for the breakage behaviour of greenhouse covering materials. Therefore, for now it is assumed that the application of thin chemically strengthened glass will not give problems for the safety of the design of the greenhouse covering.

## 8.3. Determination Structural Properties Thin Glass

In the previous section, the characteristic values for the tensile bending strength of regular and thin glass are determined. However, for thin glass these properties are not yet scientifically proven. For the application of thin glass in greenhouse coverings it is not only necessary to determine the bending strength, but also the impact strength of the panels. Currently, hail damage causes large risks and costs for greenhouse owners, as explained in the insurance section of Chapter 5. If the impact strength of thin glass is higher than that of regular glass, it might be beneficial to use thin glass over regular glass. This section treats the possibilities for determination of the two most important structural properties of thin glass panels: bending strength and impact strength.

### 8.3.1. Bending Strength

The ultimate bending strength of thin glass is currently not clearly regulated in the Dutch design standards, as explained previously. Neugebauer (2016) investigated and analysed different test configurations for their applicability for determination of the bending strength of thin glass. The different test set-ups investigated by Neugebauer are, see Figure 8.5:

- Ring on ring test
- Pressure pat on ring test
- Four point bending test
- Multiple point bending
- Bending by in-plane force
- Bending with constant radius

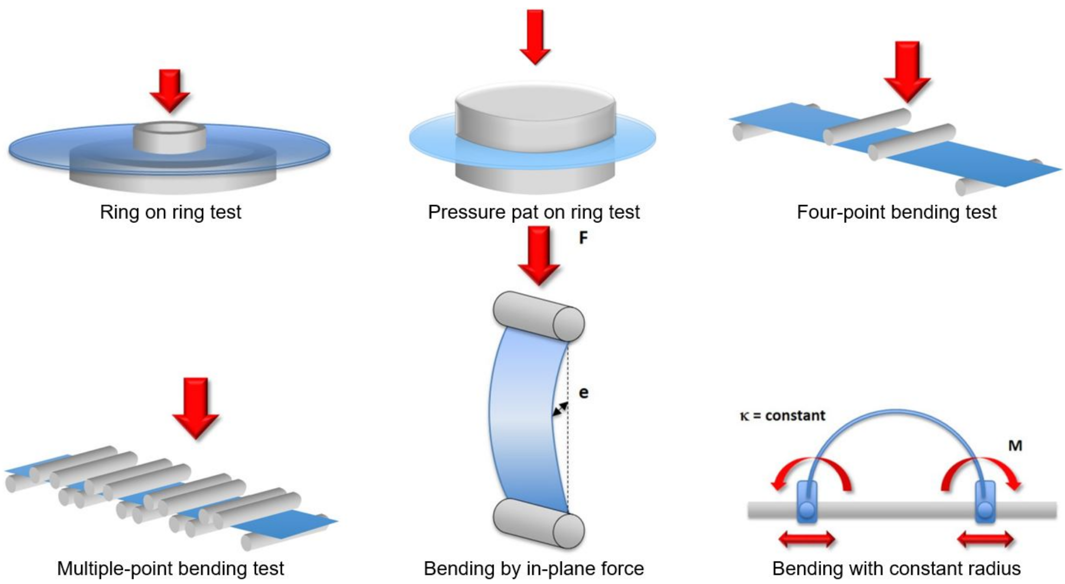



**Figure 8.5:** Visualisation of possible test configurations, image adjusted from Neugebauer (2016)

The first two configurations determine the bending strength without taking into account the influence of the edge strength. This can be used for applications where the edge effect does not have to be taken into account. An example of this application are four sided simply supported glass elements such as window glazing. The latter configurations determine the bending strength by taking into account the influence of the edge strength. This can be used for application where the edge effect has to be taken into account. An example of this application is an on two opposite sides simply supported glass element such as façade elements.

The following effects have been taken into account in the research of Neugebauer for the determination of the bending strength:

- Nonlinearity of test set-up
- Sample size
- Imperfections
- Load duration

Neugebauer states in his paper that for the determination of the bending strength of thin glass *"it is needed to find an accurate balance between size of the effective area, in which measured stress can be assumed homogeneous, and sensitivity related to imperfections and non-linear effects"*. The ring on ring test might be usable when they are improved so that the probability of stability effects is minimised. However, Neugebauer concluded in his paper that the bending with constant radius with influence of edge strength is the most promising test scenario, because it increases the homogeneous stress area remarkably when compared to the other test configurations. It should be noted that this test configuration should be investigated much more relating to its applicability for thin glass.

### 8.3.2. Impact Strength

Shutov et al. (1996) performed a research to investigate a method which can be used for calculating the impact strength of sheet glass. The research resulted in the conclusion that the dynamic strength of the glass considerably increases when the surface stress increases. Therefore, it is concluded that the tempering (or chemically threatening) of glass is a very effective way of increasing the dynamic strength. The use of thin chemically strengthened glass in greenhouse covering is therefore likely to reduce the hail damage compared to the use of the annealed float glass that is currently used.

#### Previous Research

In 1984, TNO conducted an investigation into the hail resistance of various greenhouse covering materials (KRI-TNO et al., 1984). The research investigated the hail resistance of both plastic and glass plates. A test configuration has been developed for this research in which different types of plates are placed in a representative part of a greenhouse deck and are subsequently subjected to shooting tests with plastic imitation hailstones, see Figure 8.6. The shooting tests are performed with hailstones of four different diameters: 10, 20, 30 and 40 mm. The criterion adopted during the tests is the speed at which damage, such as holes and cracks, occurs to the plate. Despite the lack of detailed information about hailstorms, the assumption is made that damaging hailstones have a diameter of 20-30 mm. From the results of this research two main conclusions can be drawn: 1) plastic panels have a better hail resistance than glass panels and 2) for these diameters (20-30 mm) the float glass panels already were damaged before the equilibrium fall velocity was reached.

#### Thin Glass

The research performed by TNO gives some insight in the behaviour of plastic and glass panels under an impact load. The results show that regular float glass is sensitive for hail damage and that it is likely that float glass panels will break during a hail storm. Recently, a trend is visible in the Netherlands of an increase of the amount and intensity of hailstorms, causing extensive costs for both insurers and greenhouse owners. The application of a material that has good light transmittance properties and a better resistance to hail, is likely to cause a reduction in risks and costs that are related to hail damage. The higher strength and flexibility of thin glass might result in a greenhouse covering that is better resistant to hail impact. However, the impact behaviour of thin glass for hail is not yet determined. A complete study on the impact strength of thin glass

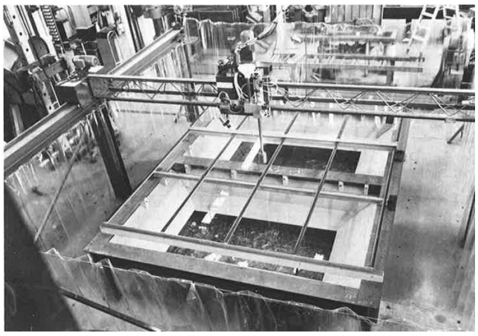


**Figure 8.6:** Measurement set-up used for the hail impact research by TNO (KRI-TNO et al., 1984)

was not possible within the scope of this research, but a short overview will be presented below for the most important factors for the determination of the impact strength of thin glass panels.

The two topics that are the most important when determining the benefits of applying thin glass in greenhouse covering to reduce the hail damage are: the stresses caused by the impact of a hail stone and the maximum impact stresses the thin glass panel can resist.

### Hail Characteristics

At this moment almost no data is available on the quantity, recurrence intervals, size, speed etc. of hail characteristic for hailstorms that occur in the Netherlands. Further hail research requires good hail data, but these are not easily measurable with ground stations because there are no automatic hail meters. At this moment, experiments use "hailpads" which are foam tables that are placed in the field. After each hail storm the amount of impact dents is counted by hand. This is a very impractical and time consuming measurement method, which results in the fact that almost no hail data is available in the Netherlands. Radar usage might be an alternative that is researched. However, when further research is performed to the feasibility of thin glass in greenhouse coverings, it is advised to set-up several of these hailpads at different location in e.g. the Westland and Brabant where large hail storms have been noticed in previous years. An alternative measurement system proposed by the author is to install a pressure sensitive plate instead of a foam pad, so that the impact characteristics such as size, speed and quantity of hail stones can be measured more accurately.

### Impact Strength

Research by Paterson and Sankaran (1994) showed that the impact process of a hailstone striking a sheet of material can be split into three main stages as shown in Figure 8.7.

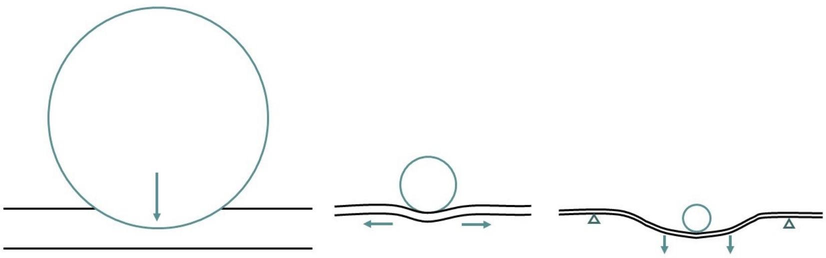



**Figure 8.7:** Visualisation of three stages during hail impact on a sheet

In the first stage, local changes near the contact area are present. The hailstone slows down and first elastic and then possibly plastic deformations occur. The local area of the plate beneath the hail stone, accelerates until both the hail and plate are moving at the same speed. Elastic and perhaps plastic stress waves, created in the second stage in the plate by the impact, are travelling away from the impact area towards the edges of the plate and rebounding. In the final stage, the plate is rotating about its supports and will behave in a quasi-static manner. During impact, the plate can deform elastically and spring back to its original shape, but it can also crack. The behaviour of the hail stone is dependent on the type of impact. When the plate is stiff, it is likely that the hailstone will deform plastically or even crack. However, the hailstone may be undamaged when the plate is flimsy, because all the hailstone energy is absorbed in plastic deformation or crack formation. The research of Paterson shows that the second stage of the hail impact is usually the stage that leads to the largest stresses in the plate.

Shutov et al. (1996) proposed a numerical method for calculating the impact strength of sheet glass by the use of a falling ball. This research shows that the increase of the surface stress, considerably increases the dynamic strength of the glass. However, this research is not yet performed for thin glass panels and therefore it can not be said whether this method is also applicable for thin glass panels. It is therefore advised to research the behaviour of thin glass panels under impact load with both numerical and experimental methods.

## 8.4. Conclusion

The research to the structural properties of thin chemically strengthened aluminosilicate glass results in the following conclusions:

- The strength of glass is high, when looking at the atomic level. However, the strength of glass is reduced by flaws in the glass surface and edges.
- Safety is an important factor when designing (greenhouse) structures that include glass. The broad range in material quality results in a large spread of tensile strength tests. This is why the characteristic values, as presented in Table 8.1, are relatively low. The design values will even be lower due to the necessity of using a material safety factor to determine a safe design value.
- Various testing procedures are presented in the Dutch design standards for the determination of the bending strength of glass. However, the Dutch design standards are developed for regular float glass and can not be directly applied for thin aluminosilicate glass.
- The characteristic bending tensile strength of thin chemically strengthened aluminosilicate glass is set to 260 MPa for this research. However, the bending strength of thin glass is not yet extensively researched. The research of Neugebauer (2016) showed that the “bending with constant radius with influence of edge strength” is the most promising testing method for thin glass. This test method should be further investigated relating to its applicability for thin glass.
- The impact strength of thin glass is likely to be higher than that of regular float glass due to the chemical strengthening treatment. However, no specific value could be determined due to a lack of data.
- At this moment almost no data is available on the quantity, recurrence intervals, size, speed etc. of hailstorms in the Netherlands. Further hail research requires good hail data, which can be obtained by using the traditional hailpads or use more advanced measurement systems such as radar or pressure sensitive plates.

# 9 Structural Behaviour

This chapter treats the structural behaviour of the thin chemically strengthened aluminosilicate glass panels for application in a greenhouse roof covering. Firstly, the used loads and load combinations are presented. Secondly, a numerical analysis of the structural behaviour of regular float glass and thin glass in the reference system is executed. The results of these analyses lead to the execution a variation study. The variants used in the variation study are shown and hereafter the execution and results of the numerical and experimental analysis are treated. Lastly, the conclusion of the research to the structural behaviour of thin glass panels in greenhouse coverings is presented.

## 9.1. Loads

The loads are determined according to the Dutch standard for greenhouse design NEN 3859 (Normcommittee 351 037 "Kasconstructies", 2012), the general Dutch standard for load determination NEN 1991-1-1 (Normcommittee 351 001 "Technische Grondlagen voor Bouwconstructies", 2002) and the ISSO 88 Quality requirements for greenhouses (ISSO Foundation, 2015). The section below treats the used loads and load combinations. The exact determination of the loads is further elaborated in Appendix D.

### 9.1.1. Design Values

The Dutch standard for greenhouse design and production (Normcommittee 351 037 "Kasconstructies", 2012, p. 29) state that for the design of greenhouses all loads and influences that are likely to occur during the design lifetime should be considered. However, the research scope is focussed on the structural behaviour of the greenhouse covering (as explained in Chapter 2) and therefore the choice is made to neglect the loads such as installation loads, crop loads and thermal loads. The loads that are considered for the research are: permanent (dead load), wind, snow, rain and hail loads.

The detailed determination of the loads is presented in Appendix D. The stresses in the panel are investigated and therefore the load factors for the Ultimate Limit State (ULS) are assumed. Normally the load factors for the Serviceability Limit State (SLS) are used for the analysis of the deformations. However, the choice is made to use the ULS load factors for both situations, which results in more conservative values for the deformations. The design values for the different loads are presented in Table 9.1.[1]

The wind load is acting perpendicular to the axis of the glass panel. The other loads (permanent, snow, rain

[1] It is important to notice that it is hard to determine the hail load because no hail data is available, as explained in Chapter 8 and Appendix D. It is possible to determine the impact energy of a hail stone, but for a representative model it is necessary to examine the extent of interaction, crushing and deflection of the hail stone and glass panel. The choice is made not to investigate this during the research, because it would be outside of the research scope. Therefore, no hail load will be used during the rest of the numerical and experimental analysis as it would give biased results.

**Table 9.1:** Resulting design values from design determination as shown in Appendix D

| Load | kN/m$^2$ |
|---|---|
| Permanent | 0.0138 |
| Wind | -0.9570 |
| Snow | 0.2520 |
| Rain | 1.0740 |
| Hail | - |

and hail) are acting parallel to the gravitational force, see Figure 9.1. The glass panel is placed under an inclination ($\alpha$) and therefore the other loads are acting under an angle on the glass panel. The permanent and wind loads are evenly distributed forces. While the snow and rain loads are triangular distributed forces and the hail load is a point load. A graphical representation of the direction and of the forces is shown in Figure 9.1.

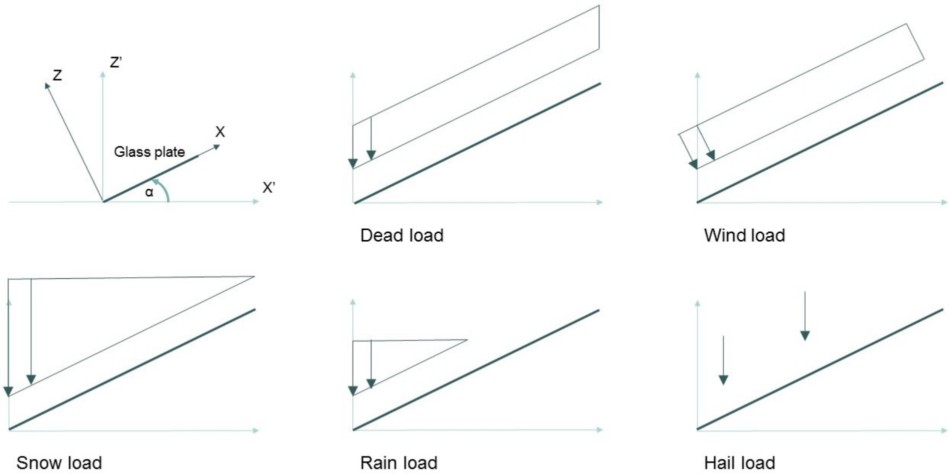



**Figure 9.1:** Visualisation of the directions of the different loads on the glass panel in the reference greenhouse system

### 9.1.2. Load Combinations

The Dutch standard for greenhouse design (Normcommittee 351 037 "Kasconstructies", 2012) states that all loads that may occur at the same time must be assessed as a load combination. However, loads that cannot occur at the same time, for example due to physical reasons, do not need to be included in a load combination. Therefore, the following load combinations are considered (based on NEN 3859 table 7):

- Permanent + wind
- Permanent + snow
- Permanent + rain

## 9.2. Reference System: Numerical Analysis

Several theoretical methods can be used for the analysis of the behaviour of thin panels. Nevertheless, the Finite Element (FE) method is generally considered to be the best suitable for including the geometrical non-linearity that is the result of the large deflections caused by out of plane loading. The use of FE models, a combination of numerical analytical techniques and computing power, makes the task of non-linear analysis feasible and solutions for complicated geometry, loading and boundary conditions can be obtained relatively easy. Nevertheless, the results from FE models should be distrusted on beforehand and analysed critically before drawing conclusions.

The goal of the research is to investigate the applicability of thin glass in greenhouse coverings. To achieve this, it is necessary to research the structural behaviour of the thin glass when applied in a greenhouse covering. A reference model is presented in Chapter 6 which shows the built-up and dimensions of a currently used Venlo roof covering system. This reference system is used to investigate which boundary conditions are required when thin glass is applied instead of regular float glass. The behaviour of the glass under the previously determined loads is studied by using a FE model. The program DIANA, developed by TNO, is used for the pre-processing, analysis and post-processing of the model.

### 9.2.1. General Approach

The following approach is used to investigate the plate behaviour of the glass covering panel. A reference model is created for the reference system to look at the behaviour of the regular applied float glass. When the deflections and stresses of this model are according to the Dutch standards, the thin glass model is prepared. First the thin glass model will have the same boundary conditions as the reference model, in order to investigate the structural behaviour when the regular glass is simply replaced by thin glass. If the deformations and stresses are not according to the standards, variation studies will be performed to find the required boundary conditions. The required boundary conditions are the conditions which ensure that the glass can resist the loads without falling out of the supporting structure.

### 9.2.2. Reference Model

The reference model is the FE model of the current used regular float glass in the reference system as stated in Chapter 6. The analysis results of this model will be used for comparison with the thin glass models. The structural behaviour of the thin glass models must be better than or comparable to the reference model in order to arrive at the best results.

#### Input

The used input data for the reference model is shown in Table 9.2 and Figure 9.2.

**Table 9.2:** Input data for reference model

| | | |
|---|---|---|
| **Geometry** | | |
| | Thickness | 4 mm |
| | Width | 1,245 mm |
| | Length | 2,175 mm |
| **Supports** | | |
| | Z translation | edges |
| | X translation | bottom left corner |
| | Y translation | bottom corners |
| **Loads** | | |
| | Permanent | evenly distributed, whole plate |
| | Wind | evenly distributed, whole plate |
| | Snow | evenly distributed, whole plate |
| | Rain | evenly distributed, part plate |
| **Material Properties** | | |
| | E | 74,000 $N/mm^2$ |
| | $\nu$ | 0.23 |
| | $\rho_{glass}$ | 2.48e-09 $T/mm^3$ |
| | Elements | curved shell |

#### Analysis

The general rule is that a linear analysis can be performed when the deformation is smaller than half of the thickness ($w < t/2$). The assumption is made that the deformations of the glass plate will be larger ($w > t/2$) and this is why there is chosen to perform a geometrical non-linear analysis.

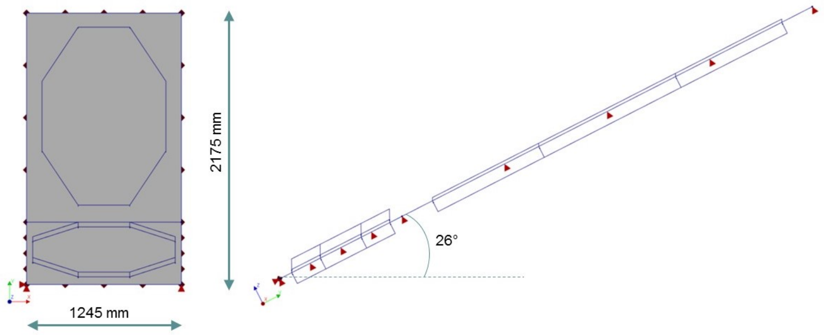
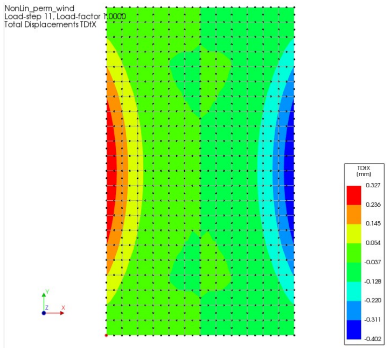


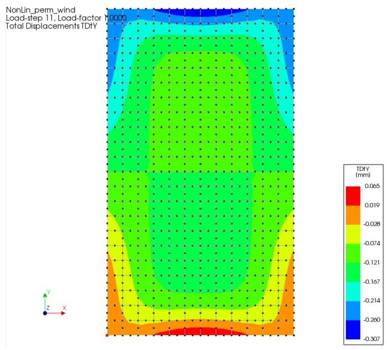

**Figure 9.2:** Overview of the geometry, orientation and loads of the reference model

## Results

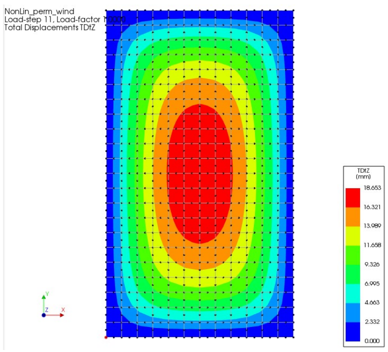
The results of the non-linear analysis of the load combination of the permanent + wind load is presented in Figure 9.3. The results of the other load combinations are presented in Appendix E.



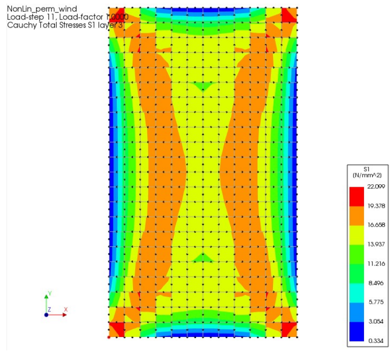

**(a)** Max TX = -0.4 $mm$




**(b)** Max TY = -0.3 $mm$




**(c)** Max TZ = 18.7 $mm$




**(d)** Max S1 = 22.1 $N/mm^2$

**Figure 9.3:** Results non-linear analysis reference model

The following can be concluded based on the results of the non-linear analysis:

**Load combinations** The results of the non-linear analysis of the different load combinations, presented in Appendix E, show that the combination of the permanent load and wind load gives the highest stresses and deformations. Therefore, the conclusion is drawn that this load combination, permanent + wind load, is the governing load combination for the greenhouse cover design. This load combination will be used for the comparison of results of the FE models from now on.

**Deformations** The maximum allowable deflections in X and Y direction are 5 mm (Normcommittee 351 037 "Kasconstructies", 2012, p. 19), because of the tolerance of the aluminium supporting structure. The maximum translations in X and Y direction are smaller than 5 mm and therefore fulfil the requirements.

**Stresses** The maximum allowable tensile stress of heat strengthened glass is 40 MPa and for fully tempered glass is 80 MPa, as shown in Chapter 8. The maximum principal stress is smaller than 40 MPa and therefore the stress requirement is fulfilled.

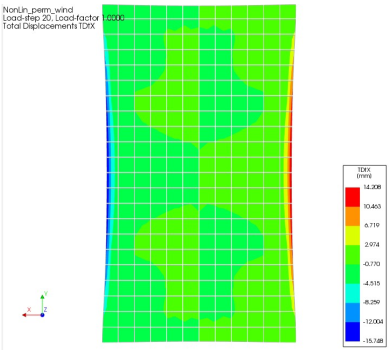
### 9.2.3. Thin Glass

#### Input

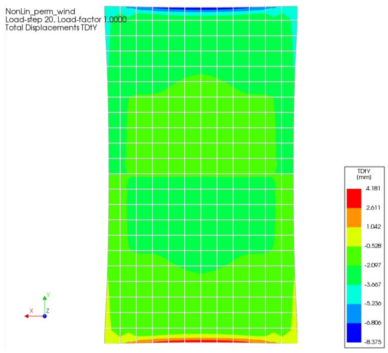
The input data for the thin glass model is almost the same as the input data for the reference model that is shown in Table 9.2 and Figure 9.2. The only adjustment for the input data with respect to the reference model is the thickness of the panel. The thickness for the thin glass panel model is 0.55 mm.

#### Results

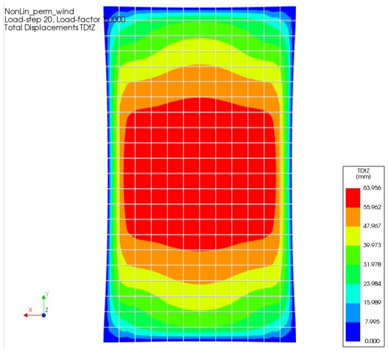
The results of the non-linear analysis of the load combination of the permanent + wind load is presented in Figure 9.4.



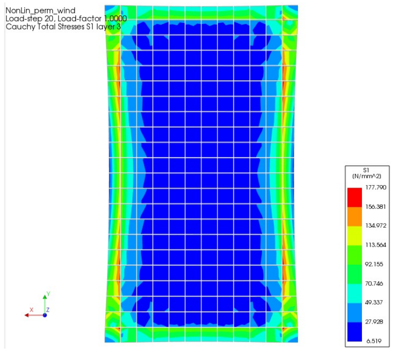

**(a)** Max TX = -15.7 $mm$




**(b)** Max TY = -8.4 $mm$




**(c)** Max TZ = 64.0 $mm$




**(d)** Max S1 = 177.8 $N/mm^2$

**Figure 9.4:** Results non-linear analysis thin glass model

The following can be concluded based on the results of the non-linear analysis:

**Deformations** The maximum allowable deflections in X and Y direction are 5 mm (Normcommittee 351 037 "Kasconstructies", 2012, p. 19), because of the tolerance of the aluminium supporting structure. The maximum translations in X and Y direction are larger than 5 mm (resp. -15.7 and -8.4 mm) and therefore do not fulfil the requirements. These deflections result in loss of structural integrity of the system and the thin glass plate is likely to slip out of the supporting structure.

**Stresses** The stresses in the plate are larger than in the reference model, but this is no problem because the strength of the material is also increased due to the chemical tempering. However, peak stresses are present at a point that is 10 mm in x and 10 mm in y direction inwards from the corner point and are likely to be caused by the double curvature of the panel. These stresses are not likely to cause failure because they do not exceed the assumed maximum tensile strength of 260 MPa for Leoflex panels, see Chapter 8.

### 9.2.4. Conclusion

For the reference model, the maximum resulting deflections and stresses are lower than the maximum allowable deflections and stresses. The conclusion is drawn that the model is prepared correctly. A short study for the influence of mesh refinement and supporting stiffness is executed, but this did not result in significant differences. Therefore there is chosen to continue with this model as a basis for the next models that will be prepared, without mesh refinement or supporting stiffness.

However for the thin glass model, the deflections in X and Y direction do not fulfil the requirements which may eventually lead to falling out of the panel. It is therefore necessary to search for a solution for increasing the stiffness of the panel, so that the deflections are kept below the acceptable range of 5 mm.

## 9.3. Variation Study: Numerical and Experimental Analysis

In the previous section, the numerical analysis of regular float glass and thin glass in the reference system is shown. The results show that for the thin glass model the deformation in X and Y direction are exceeding the allowed deformations of 5 mm that are defined in the Dutch design standards. It is necessary to execute a variation study in order to research the possibilities for reducing the deformations for thin glass panels.

The goal of the variation study is to research several possibilities for stiffening a flat glass panel to reduce the deformations, so that they are not exceeding the maximum values. The different steps of the variation study are presented in this section. Firstly, the choice for the researched variations is explained. Hereafter a numerical analysis is performed for each variation. The results are treated and a choice is made for the variations that will be used for the experimental analysis. Then the experimental analysis is explained and the results are shown. Finally, the results of the experimental and numerical analysis are compared.[2]

### 9.3.1. Variants

Two main methods are distinguished for the stiffening of a flat panel: adjusting the support conditions and stiffening the plate itself.

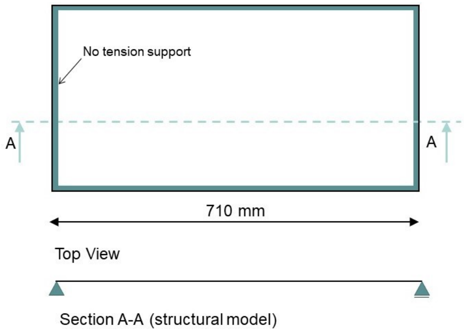
For the first method, the choice is made to look into the changes that occur by adjusting the simple supports to clamped supports. A clamped support is likely to decrease the deformations of the edges in X and Y direction to zero. This will lead to lower deformation in Z direction in the middle of the plate, but the stresses might increase due to the clamping of the edges.

For the second method, the choice is made to research the following stiffening possibilities:

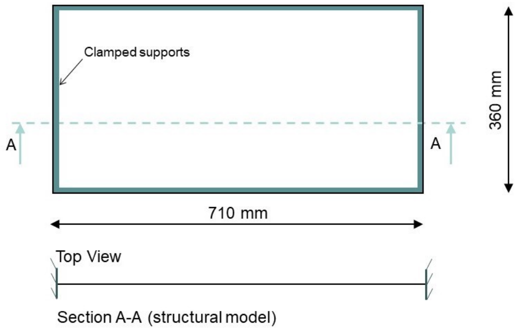
- Glueing rib as a stiffener,
- Using cable sub-structure to get a subtended structure,
- Increasing moment of inertia by making a sandwich structure of two glass panels,
- Using the enclosed air layer in an insulating glass unit (IGU).

[2] The available sizes for the panels that can be tested are 360 x 710 mm with a thickness of 0.55 mm. The choice is made to perform the numerical analysis for panels of this size, so that it is possible to compare the numerical and experimental results.

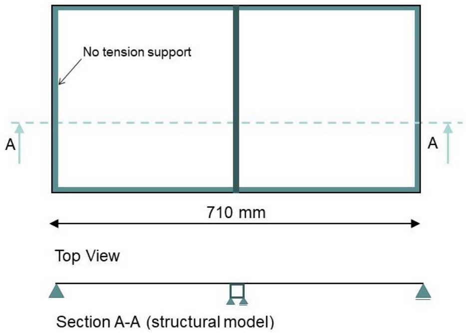
Figure 9.5 shows an overview of the different variants, the exact configurations of the ribs and TSSA patches were determined by a short optimisation research.



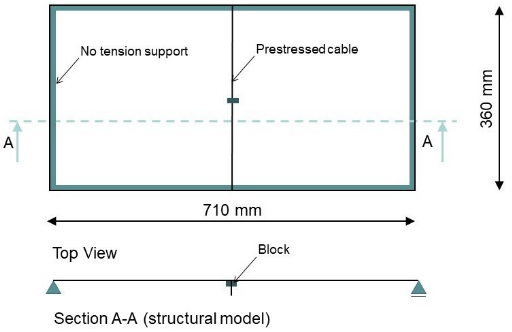

**(a)** Simply Supported Reference Model



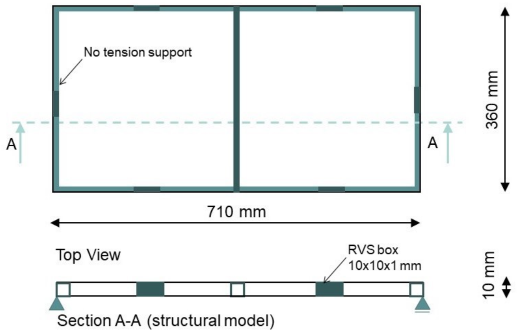

**(b)** Adjusted Supports Variants



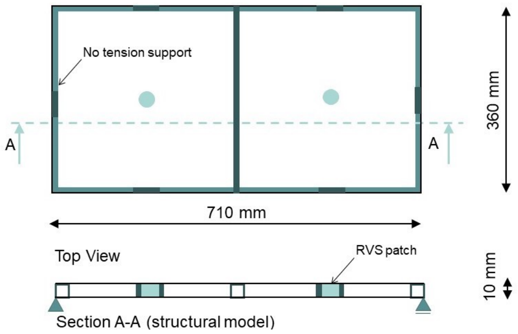

**(c)** Single Plate Rib Stiffener



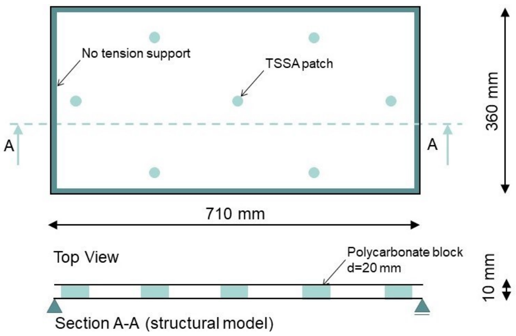

**(d)** Single Plate Cable Stiffener



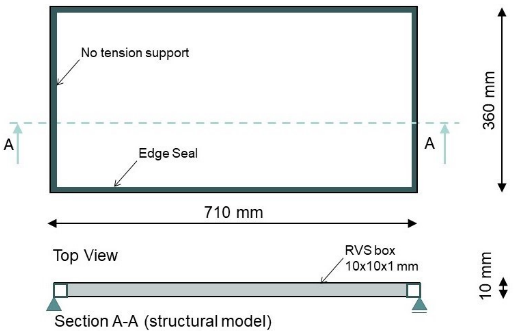

**(e)** Sandwich Plate Box Sections




**(f)** Sandwich Plate Box Sections and Patches




**(g)** Sandwich Plate TSSA and Polycarbonate patches




**(h)** Insulated Glass Unit

**Figure 9.5:** Overview of variations study options for stiffening glass panel

## 9.3.2. Numerical Analysis

The FE method is generally considered to be the most adaptable for including the geometrical non-linearity that is the result of the large deflections caused by out of plane loading, as explained previously. The choice is made to first analyse the structural behaviour of the different variants after which the most promising variations will be tested experimentally.

First the general used input data for the FE model is shown. Then the results of the non-linear analysis are shown for each variant. The choice is made to show the deflections at midspan and a quarter at the bottom of the panel, because in the experiment the deformations will also be measured at these points.

### General Input Data

**Geometry and Load**
The general used geometry is 360 x 710 mm and the thickness of a single glass panel is 0.55 mm. The supports are different for each variations, however in general the supports are placed at 10 mm distance inwards from the edges.

The loads are applied on the top panel, however the load application is slightly different for the IGU variant. The hermetically sealed cavity in an insulating glass unit ensures that a certain degree of cooperation between the two blades is present. The external load can therefore be divided between both glass sheets for regular float glass according to NEN2608. For a short load (such as a wind load) it is assumed that the two panels of the IGU have a 100% cooperation. Therefore half of the load that is used for the other variants is applied on the top and bottom panel in the FE model of the IGU variant. An additional experiment is performed on the IGU panel to check if the assumption stated in NEN2608 is also valid for an IGU with thin glass panels. The description of the additional experiment is presented in Appendix F. The deflection at midspan are measured for the top an bottom panel. The results presented in Appendix F in Figure F.11, show similar results for the deflection of the top and bottom panel. Therefore it is concluded that the design rule for the load distribution over the two panes can be used for the numerical analysis of the IGU panel.

The loads are applied at multiple faces over a total area of 270 by 600 mm. The loads are applied in multiple phases, so that the load application corresponds as much as possible with the load application that is used in the experiment, see Appendix F. The total distributed load ($q_{load}$) is acquired by applying a load with a total weight of 500 grams in the middle of the plate ($q_{load,mid}$), then at the left side of the plate ($q_{load,left}$) and finally at the right side of the plate ($q_{load,right}$). This sequence is repeated until the required total load is reached (9 kg). An overview of the used geometry and loads is presented in Figure 9.6.

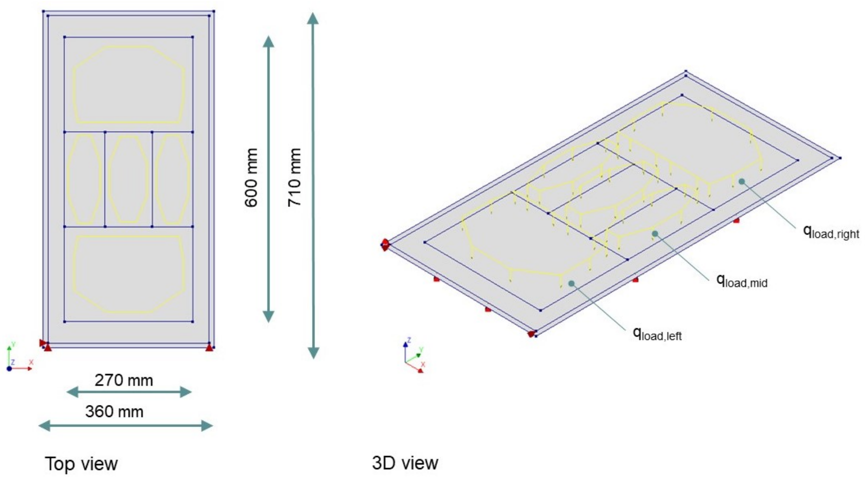



Figure 9.6: Overview of the geometry and loads of the variation models

**Analysis**
Two different analysis are performed for each model. First a linear analysis is performed to check the overall

quality of the model. Hereafter, a geometrically non-linear analysis is performed, because of the large out-of-plane deformations with respect to the thickness of the panel.

The choice is made to show the resulting deflections at midspan (coordinates: x = 180, y = 355) and a quarter (coordinates: x = 180, y = 532.5) at the downside of the panel in a load-displacement graph, because the deformations will also be measured at these points in the experiments. The locations of the measurement points are shown in Figure 9.7.

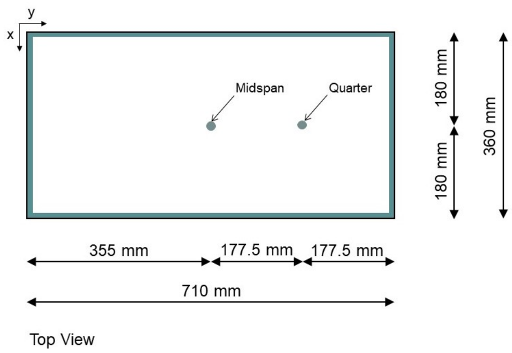



**Figure 9.7:** Overview of the measurement locations for the variation study

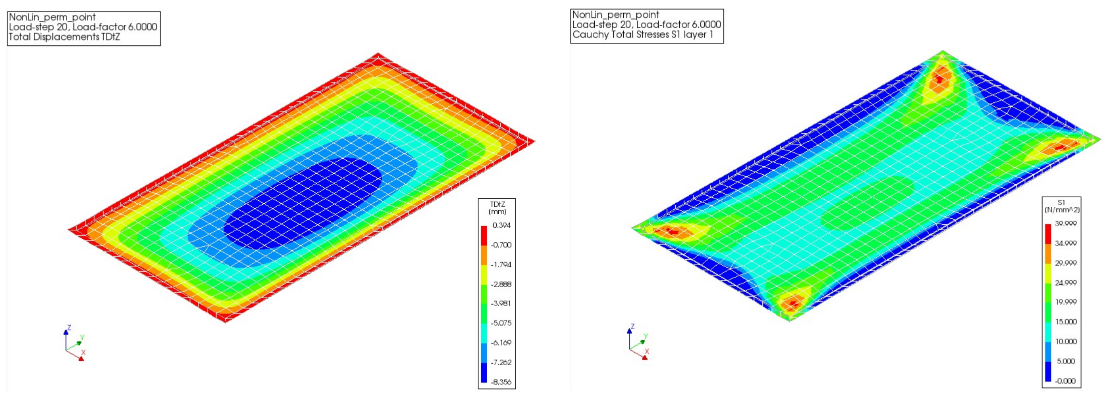
**Material Properties**
An overview of the used material properties and elements for the different materials is presented in Table 9.3.

**Table 9.3:** Overview of used material properties and elements for FE variation models

| | Glass | Stainless Steel | Polycarbonate | |
|---|---|---|---|---|
| $E$ | 74,000 | 200,000 | 2,500 | $N/mm^2$ |
| $\nu$ | 0.23 | 0.29 | 0.37 | – |
| $\rho$ | 2.48e-09 | 8e-09 | 1.2e-09 | $T/mm^3$ |
| Elements | Curved shell | Solid | Solid | – |

## Results

**Simply Supported Reference Model**
The simply supported reference model is slightly adapted from the reference model as shown in the previous section. The adjustments are made so that the boundary conditions of the FE model match the conditions of the experiment as much as possible. An area of 10 mm width along the edges is used for the application of non-tension boundary conditions. This means that the plate is supported in negative z direction in this area, but the plate can move in positive z direction.




**(a)** Max TZ = -8.4 $mm$ **(b)** Max S1 = 40.0 $N/mm^2$

**Figure 9.8:** Results non-linear analysis simply supported reference model (total load is 9 kg)

The contour plots of the resulting load steps in Figure 9.8 show that the maximum deformation is -8.4 mm in the middle of the plate. The maximum stresses are visible in the corners of the plate, however the stresses are much lower than the maximum tensile strength of 260 MPa for the thin glass. Figure 9.9 shows the deformations in z direction of the locations a midspan and a quarter during the load increments. These values will be used as a reference for the other FE models for the variation study.

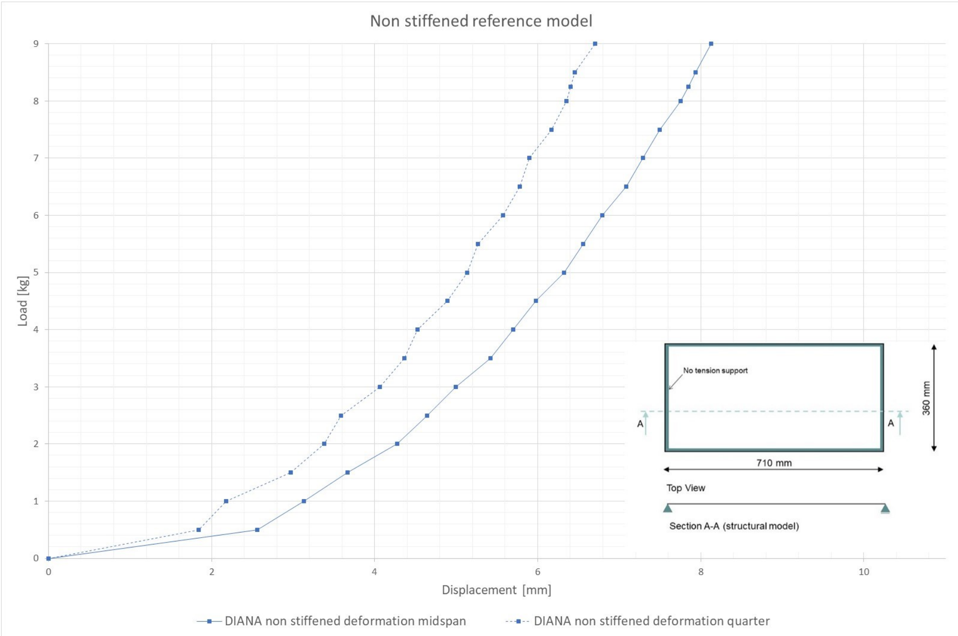



**Figure 9.9:** Resulting graph of the displacements at midspan and a quarter for simply supported reference model

**Adjusting Support Conditions**
Four different variants are tried out with the numerical analysis to check which of these variants gives the best results:

- 4 edges: fixed translations and rotations
- 4 edges: fixed translations, free rotations
- 2 long edges: fixed translations, free rotations
- 2 short edges: fixed translations, free rotations

The contour plots of the results for the different variants at a total load of 9 kg are shown in Appendix G. The resulting deformation at midspan and a quarter for the different variations are shown in Figure 9.10. From the results in Figure 9.10 it can be seen that the deformations in z direction for the fixing of only the short or long sides are almost similar to that of the simply supported plate. The fixing of the four sides of the plate does significantly reduce the deformations. Almost no difference is visible in the deformations between fixing only the translations or both rotations and translations. However, larger stresses occur at the edges when both rotations and translations are fixed. The choice is therefore made to execute only one experiment for the adjusted support conditions: the fixations of all four sides.

**Stiffening Plate Itself**
The contour plots of the results for the different variants at a total load of 9 kg are shown in Appendix G. The resulting deformation at midspan and a quarter for the different variations are shown in Figure 9.11.

The results in Figure 9.11 show that:

- The resulting load-displacement graphs of the DIANA analyses show non-linear behaviour. The previously made assumption for the application of a geometrical non-linear analysis can be justified by the non-linear results from the DIANA analyses.
- All of the variations have lower deflections than the simply supported reference model.

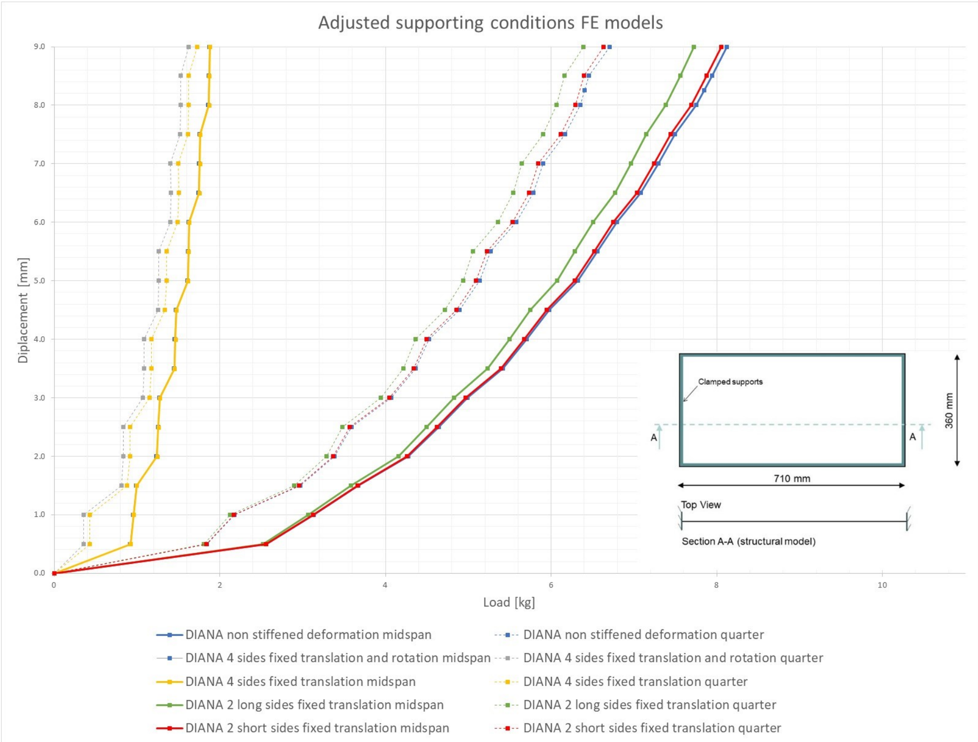



**Figure 9.10:** Resulting graph of the displacements at midspan and a quarter for the adjusted support models

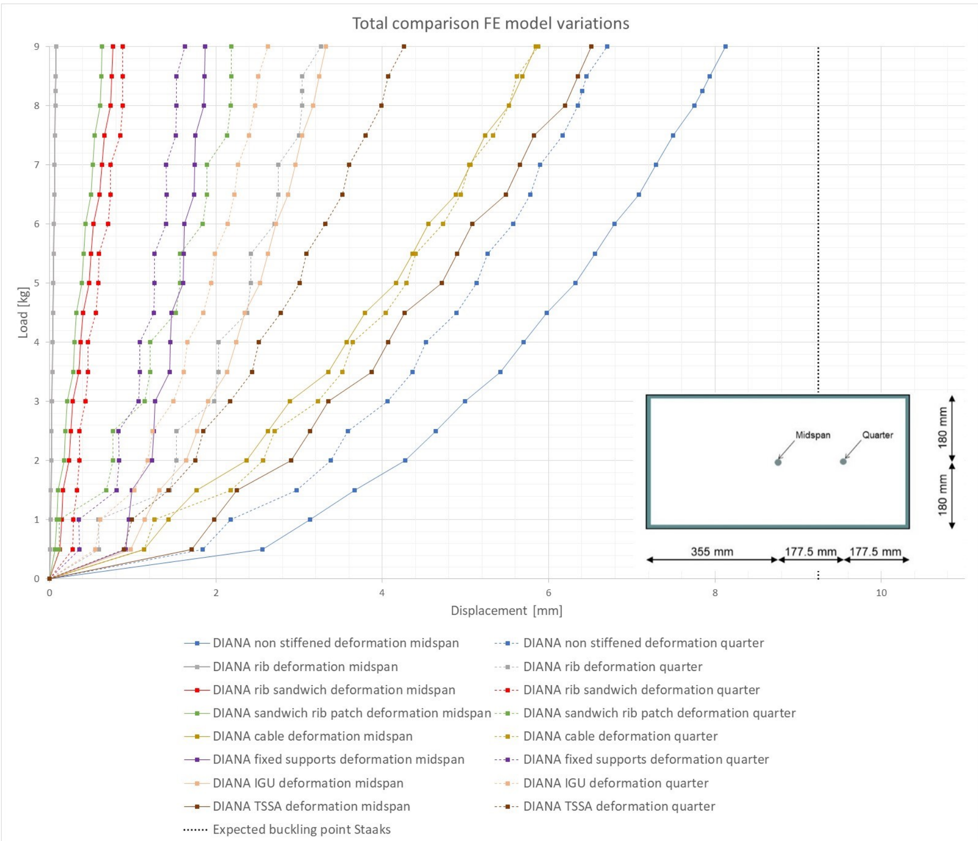



**Figure 9.11:** Resulting graph of the displacements at midspan and a quarter for the stiffened variation models

- The deformation of the cable supported plate are very depending on the applied pretension of the cable. It is therefore necessary that this pretension is measured when the experiment is executed.
- The deformation for the plate with one rib is very small at midspan, but the deformations at a quarter are much larger.
- For the sandwich construction without a patch, it is visible in the contour plots that the deflection of the top plate is much larger than the bottom plate. This is why the decision is made to also make a sandwich panel with a patch in the middle that provides a better cooperation between the two panels. It is visible in the graph that the deformation of the patch sandwich model at a quarter is larger than without patch, because the deformation of the bottom panel is measured.
- The sandwich panel with TSSA and polycarbonate patches reduces the deflections, but is still the least stiff option of all the variants mentioned in Figure 9.5.
- The IGU panel results in larger deformations than the clamped and rib stiffened sandwich panels. However, the influence of the enclosed air layer is significant and therefore it is expected that insulated sandwich panels will behave stiffer when an edge seal is used.

The choice is made to execute experiments for six of the variants that are presented in Figure 9.11: non stiffened, rib, rib sandwich, rib sandwich patch, cable and fixed supports. The experimental analysis is shown in the next section.

### 9.3.3. Experimental Analysis

The small scale experiments are executed on panels of 360 by 710 mm. The numerical analysis, treated in the previous section, is also executed for this size.

#### Experimental Set-up Description

**(a)** Top view

**(b)** 3D view with distributed load

**Figure 9.12:** Overview of simply supported experiment set-up

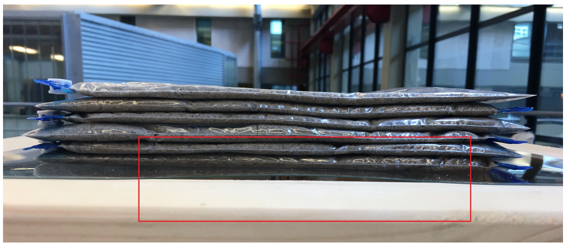
The detailed explanation of the approach, set-up and execution of the experiments is shown in Appendix F. The set-up of the experiments for the small plates consists out of a wooden frame on which the plates are placed. Two linear potentiometers are placed at the centre and a quarter of the plate and measure the deflection in z direction. The load is applied by placing the sand bags of 0.5 kg next to each other on the plate until a total load of 9 kg is applied. In total 7 different variants are tested: simply supported, four sides clamped, one layer with supported rib, cable supported, rib sandwich, rib sandwich with additional patches and insulated glass unit. The set-up for the simply supported experiment is shown in Figure 9.12.

#### Results

The results of the experiments are presented in this section. First the visual observations are treated. Hereafter, the resulting deformations are presented in a load-displacement graph. Finally ,the resulting deformations are shortly discussed.

**Visual Observation: Buckling**
During the experiments out-of-plane buckling behaviour of the plate was observed, as shown in Figures 9.13a and 9.13b.

**(a)** Long edge



**(b)** Short edge

**Figure 9.13:** Buckling edges during loading simply supported plate, visible in red frame

Staaks (2003) researched the out-of-plane behaviour of twisted glass plates and observed a change of mode from double curvature to single curvature when the out-of-plane deformation became too large. The out-of-plane deformation at which this change of mode is expected is determined by Staaks and can be calculated by Equation 9.1.

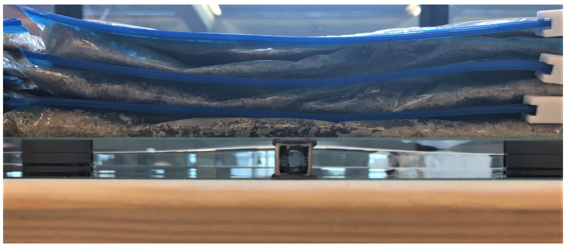
$$dz_{buck} = \alpha_{Staaks} * t \tag{9.1}$$

In which $\alpha_{Staaks}$ is the buckling factor of 16.8 according to Staaks and $t$ is the thickness of the plate in $mm$.

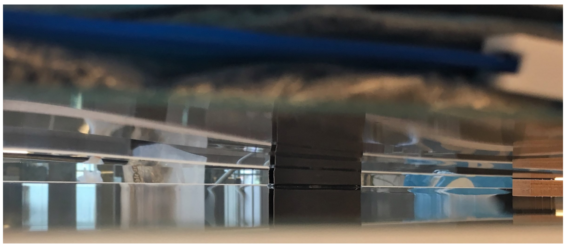
For the simply supported panel it is therefore expected that out-of-plane buckling will be visible at a deformation of 9.24 mm. Figure 9.15 shows the deformations of the variation experiments in z direction during the incremental loads for midspan and quarter locations. It can be seen that buckling of the simply supported plate at midspan occurs at the predicted deformation according to Staaks. Therefore, it is assumed that the out-of-plane buckling during the experiment can be explained by the change of double curvature to a single curvature.

**Visual Observation: Top Plate Deflection**

In the experiment of the rib sandwich panel it is noticed that the deflection of the top plate was much larger than the deflection of the bottom plate. In Figures 9.14a and 9.14b it is tried to show the difference in curvature of top and bottom plate by the different reflections. This shows that not sufficient cooperation between the two panels was reached and thus an additional variant was added with a patch to increase the cooperation.



**(a)** Middle of plate



**(b)** Right side of plate

**Figure 9.14:** Reflections inside loaded sandwich panel to show difference in deflection top and bottom plate

**Test Results**

The deflections of the different experiments in z directions as measured by the linear potentiometers at midspan and a quarter are presented in Figure 9.15.

The results in Figure 9.15 show that:

- All of the plates show non-linear behaviour. This behaviour can be explained by the fact that the glass panel has a behaviour that is similar to a membrane, which means that forces perpendicular to the surface are resisted by in-plane tension forces. These membrane forces result in non-linear behaviour of the glass panel and thus the glass pane acts much stiffer than might be expected on a simple linear calculation.
- All of the variations have lower deflections than the simply supported non stiffened panel

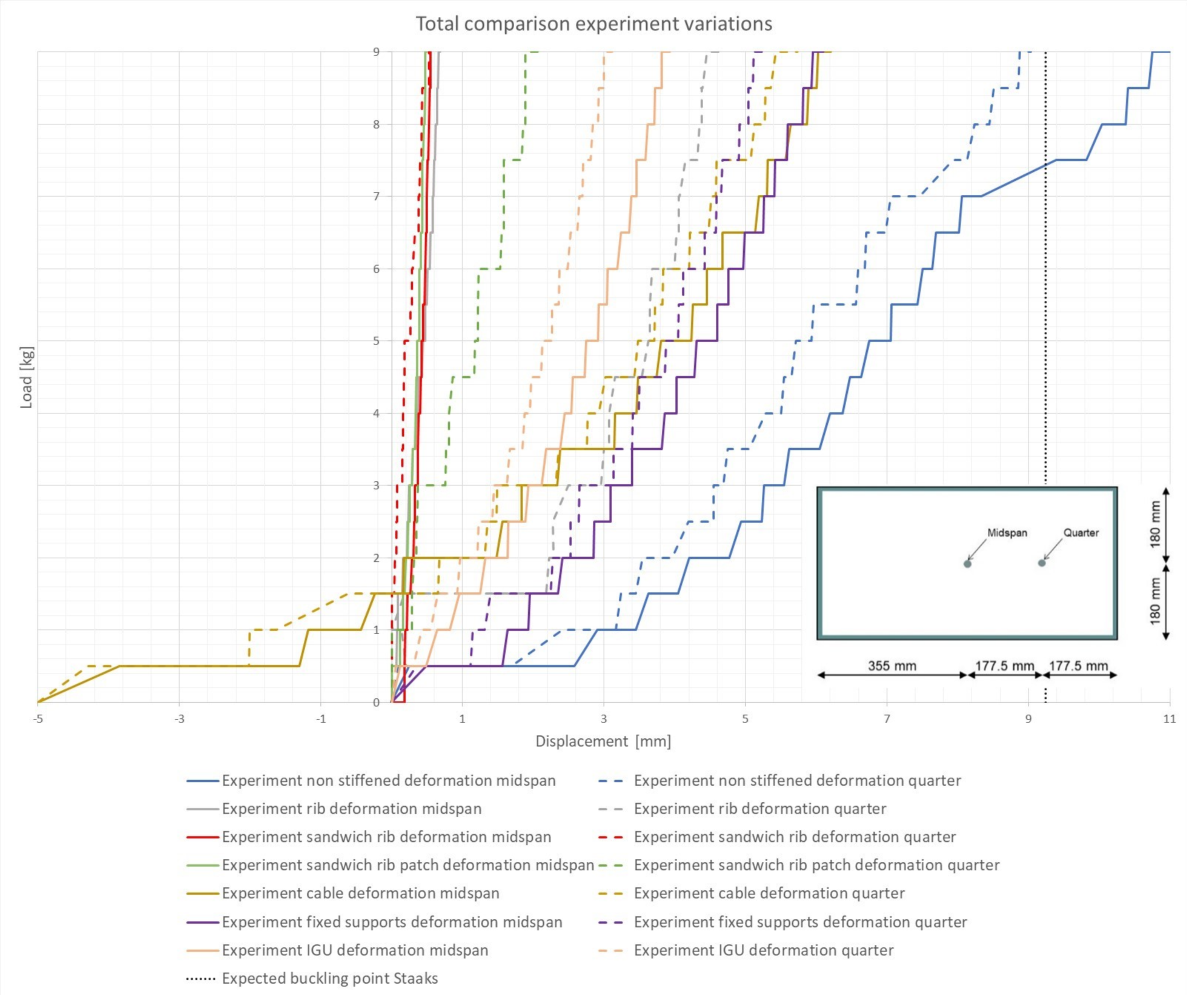



**Figure 9.15:** Resulting graph of the displacements at midspan and a quarter for the executed experiments

- Out-of-plane buckling occurs at the edges of the simply supported plate when the maximum deflection is comparable to the expected buckling deformation of Staaks.
- A relative large difference in deflection at midspan and a quarter is visible for the rib supported plate.
- The deflections at a quarter for the sandwich with patch is larger than the deflections of the sandwich without a patch. This can be explained by the fact that the deformation is measured at the bottom plate. The sandwich plate without a patch shows large deformations at the top plate,but these are not measured as explained previously. The sandwich plate with a patch has a better cooperation between the top and bottom panels, which results in larger deflections of the bottom panel at a quarter.
- The cable supported plate was curved upwards due to the pretension of the cable. Negative deflections are visible in this graph from start of loading until a load of 1.5 kg. Positive deflections are visible from a load of 1.5 kg. However, the deflections are still relatively large due to the difficulty of maintaining sufficient pretension.
- The fixed plate had relatively large deflections, which show that it is likely that no fully clamped conditions are reached during the experiment.
- The hermetically enclosed air layer of the IGU increases the stiffness of the panel.

## 9.3.4. Comparison Numerical and Experimental Analysis

The comparisons of the numerical and experimental results for each individual tested panels are shown in Appendix G. The comparisons of the simply supported plate, the plates with the adjusted support conditions and the executed variants for stiffening the plate itself are presented in this section.

### Simply Supported

The deformations of both the numerical analysis and experiment for the simply supported plate are shown in Figure 9.16.

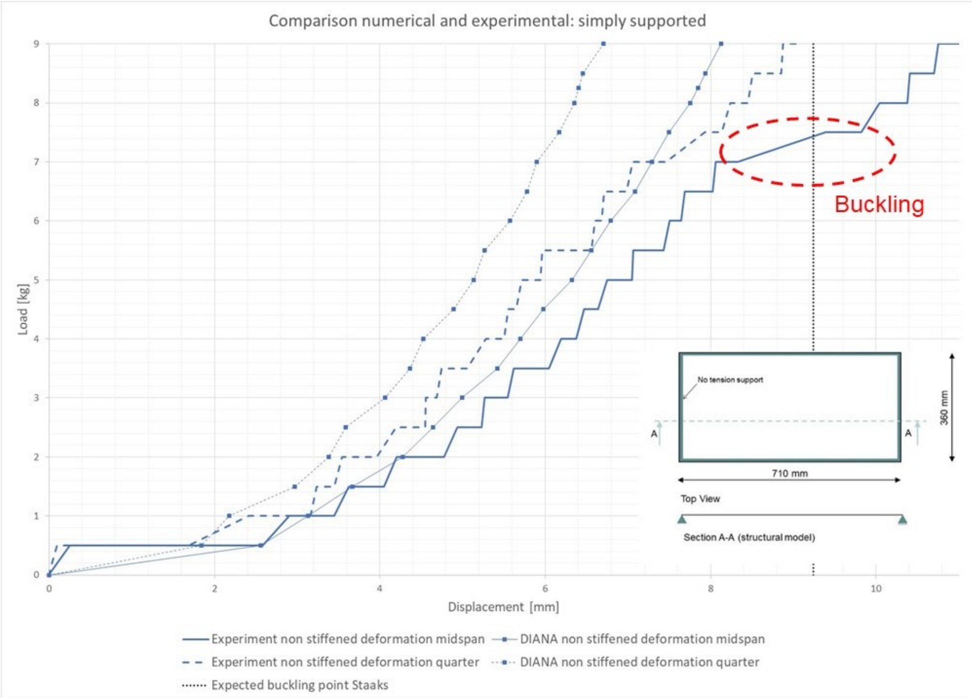



**Figure 9.16:** Resulting graph of the displacements at midspan and a quarter for the executed simply supported experiment and the related FE model

The results in Figure 9.16 show that the deformations of the FE models match the results of the experiment quite well. However, a difference in deformations is visible when buckling occurs (around a load of 7.5 kg). No out-of-plane buckling is present in the FE model and therefore the results from the buckling point onwards do not match the results of the experiment. However, it is likely that the out-of-plane buckling can be explained by the change of double to single curvature as researched by Staaks and explained in the previous section. A short study is performed to the buckling behaviour of the FE model, but changing the boundary conditions, element size or element types did not result in buckling behaviour of the FE model. No further research is performed on the modelling of the out-of-plane buckling behaviour, but it is recommended to perform a more detailed study on the modelling of the out-of-plane buckling of thin plates in the future.

### Adjusted Support Conditions

The deformations of both the numerical analysis and experiment for the plate with adjusted supporting conditions are shown in Figure 9.17.

The results in Figure 9.17 show that the deformations of the experiment are different than the deformations of the fixed FE models. The deformations of the experiment are smaller than the deformations of the two sides fixed models, but are larger than those of the four sides fixed models. It can therefore be concluded that no fully fixed conditions are reached during the experiment, but that a condition in between fully fixed and simply supported conditions is achieved. During the experiment the plate was clamped to prevent rotation and and the translation was prevented by friction due to this clamping. It is hard to distinguish if there was any in-plane translation by analysing the pictures made during the experiment. However, the difference in the results of the numerical and experimental results are likely to be caused by the fact that the friction was not big enough and therefore in-plane translation was still possible. The difference in the numerical and experimental results show that it is hard to reach fully fixed supporting conditions for a thin glass plate, but

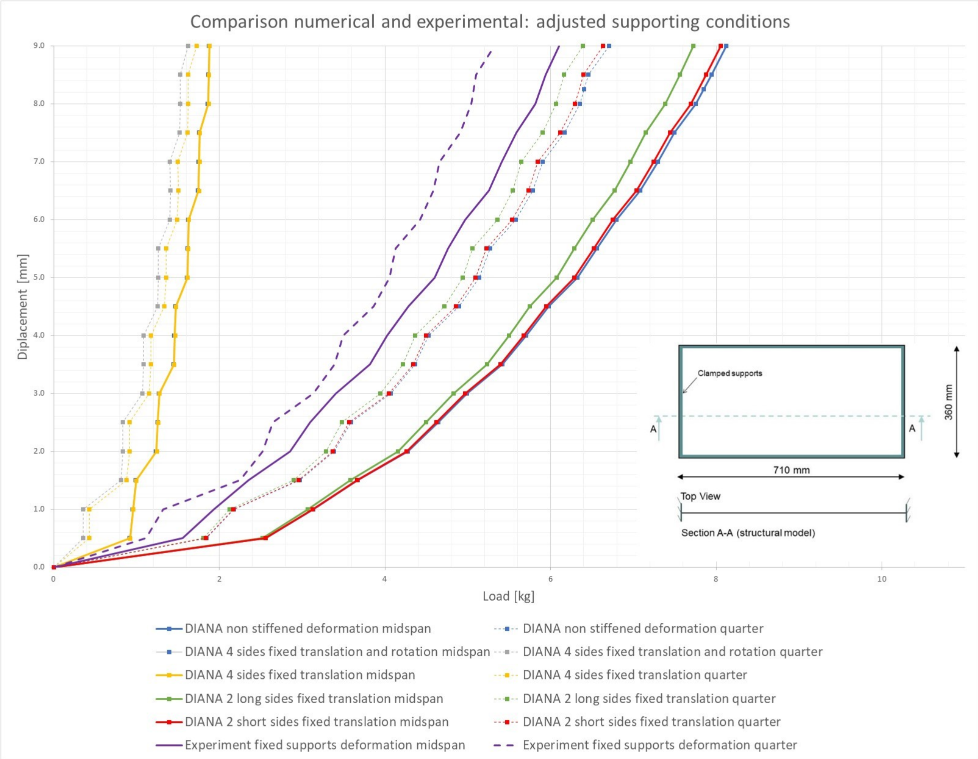



**Figure 9.17:** Resulting graph of the displacements at midspan and a quarter for the executed clamped plate experiment and the related FE models

that small translations or even rotations have a large influence on the behaviour of the plate. Therefore it is important to take these findings into account for a final design of the supports.

### Stiffened Panels

The deformations at midspan of both the numerical analysis and experiment for the stiffened plate variations are shown in Figure 9.18. The deformations at quarter of both the numerical analysis and experiment for the stiffened plate variations are shown in Figure 9.19.

The results in Figure 9.18 and 9.19 show that:

- The assumed geometrical non-linearity is visible in the results of both the numerical and experimental analyses. The out-of-plane loads are resisted by in-plane tensile forces, which lead to membrane forces. This results in a stiffer behaviour of the glass panel when compared to a linear glass element and the necessity of using geometrical non-linear analysis methods for the numerical analysis.
- All of the tested variants have a higher stiffness (lower deflection) than the non stiffened panel.
- The experimental results of the rib stiffened single panel are different than the numerical results. This can be caused by the fact that the z supports of the rib could have moved slightly, while this was fixed in the numerical analysis.
- The results of the experiments of both rib sandwich structures are very good comparable with the results of the numerical analysis of these panels. Therefore it is concluded that the FE models for these variants are accurate and can be used for further research.
- The results of the cable supported plate experiment are different than the numerical analysis. The plate had an initial curvature during the experiment due to the pretension of the cable. This initial curvature was not present in the numerical model. The results are therefore different at the start of the loading.
- The results of the experiments of the IGU panel are good comparable with the results of the numerical analysis. This shows that the assumption used for the numerical analysis regarding the load distribution over the two panels due to the hermetically enclosed air layer is correct. It is concluded that the FE model for this variant is accurate and can be used for further research.

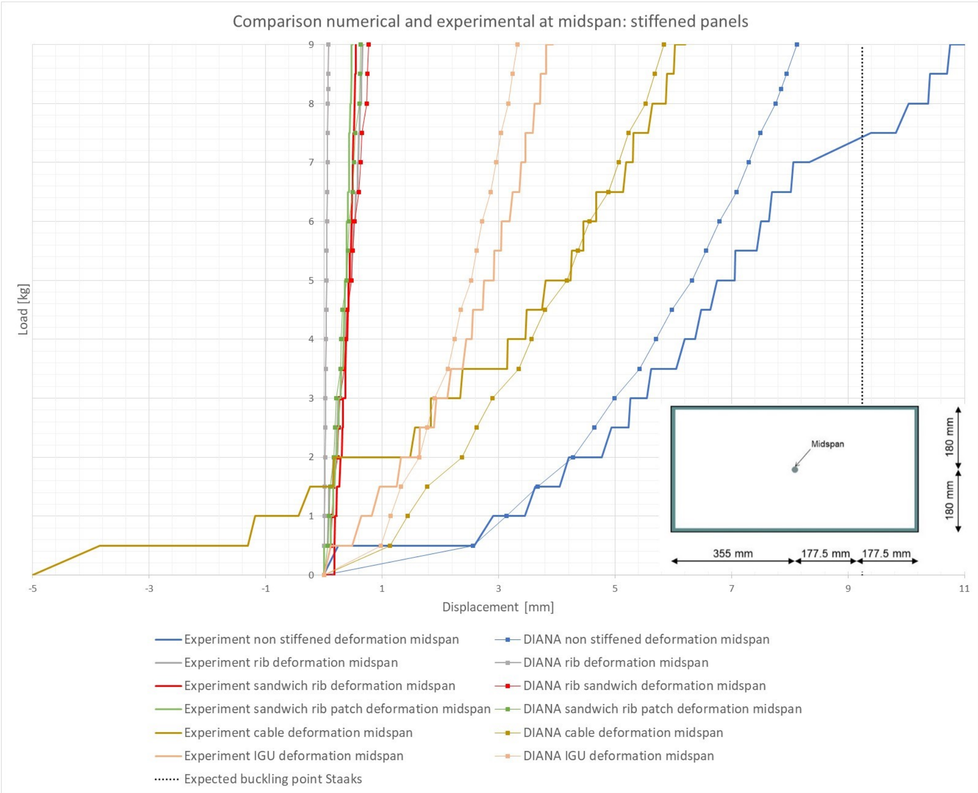



**Figure 9.18:** Resulting graph of the displacements at midspan for the executed stiffened panels experiments and the related FE models

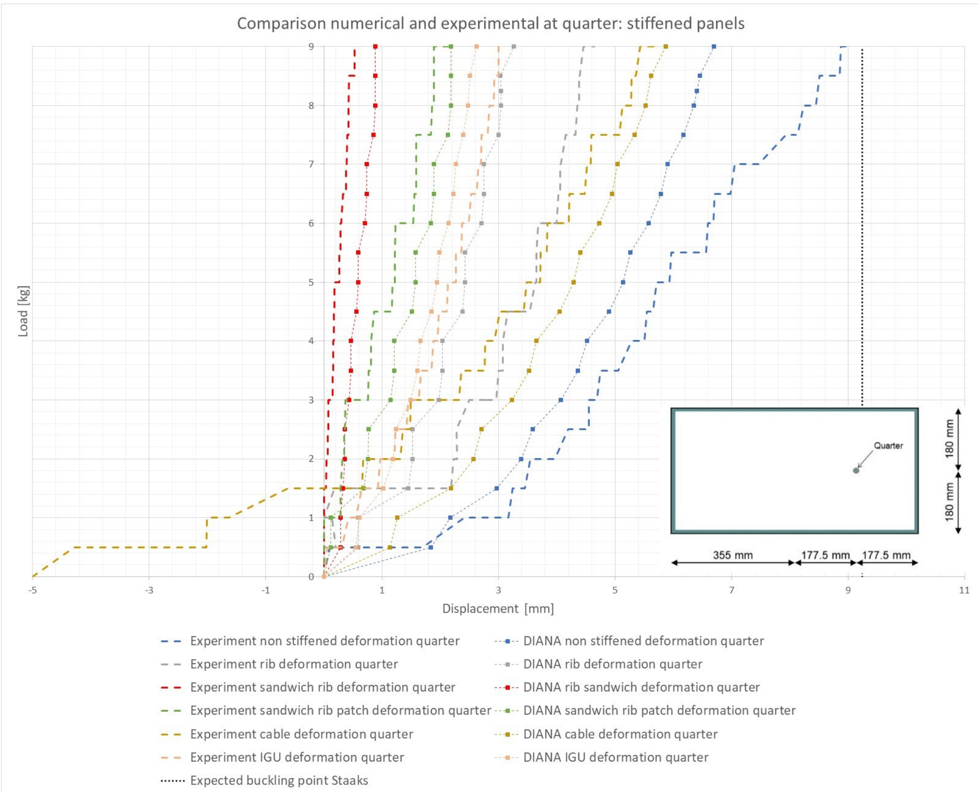



**Figure 9.19:** Resulting graph of the displacements at quarter for the executed stiffened panels experiments and the related FE models

## 9.4. Conclusion

The total overview of the results of all of the executed experiments and FE models is shown in Figure G.18. The following conclusions can be drawn from the numerical and experimental studies to the structural behaviour of flat thin glass panels:

- The results of the FE models are in general comparable to the results of the experiments. Therefore it is concluded that the FE models are built-up correctly and can be used for the estimation of the behaviour of flat thin glass panels.
- The out-of-plane buckling behaviour is not present in the FE models. It is recommended to research this behaviour more into depth in a future study.
- The boundary conditions have a big influence on the behaviour of the plate. Small changes in these conditions will result in large difference in the behaviour of the plate.
- The in-plane deformations in the x and y direction of a non stiffened thin glass panel in the reference system are exceeding the maximum values allowed according to the Dutch design standards. The maximum values are based on the supporting width of aluminium greenhouse systems. Exceeding these values may cause the panel to fall out of the aluminium supporting system. Stiffening of the thin glass panels is necessary to decrease the deformations of the panel due to an evenly distributed load.
- Changing supports to fixed supports will decrease the deflection, but in practice it is hard to realise fully fixed conditions.
- The sandwich structure has the lowest deflections and this suggests that this variant is the best way to stiffen a thin glass panel. However, the IGU structure also has a high stiffness, but without the necessity of light blocking spacers in the middle of the plate. For the feasibility of the greenhouse design the increase of the incident light is more important than the deflection in z direction. The deformations of the IGU panel are slightly larger than the sandwich panels, but the IGU panel has a higher light transmittance because no light blocking elements are necessary. Therefore it is concluded that the use of an IGU system with a hermetically sealed layer is the best way to stiffen a thin chemically strengthened aluminosilicate panel for the use in greenhouse coverings.

The numerical and experimental research performed in this chapter provided a better insight in the behaviour of thin glass panels and various stiffening possibilities. However, the variation studies are performed on small scale panels and can not simply be extrapolated to full scale applications without looking at the structural behaviour of the full scale panel. Therefore it is necessary to perform a study on full scale on the design of a full scale flat thin glass panel for application in a greenhouse covering that fulfils the requirements. This research will be performed in Chapter 11.

# 10 Economics

This chapter addresses briefly the economic aspects of the application of thin chemically strengthened aluminosilicate glass in greenhouse coverings. Firstly, the current development of the Dutch horticultural sector is shown. Secondly, an overview of the various costs in a greenhouse system are presented. Then a qualitative comparison between the application of regular and thin glass in a greenhouse covering is given. Hereafter, a short study is performed to determine the price of thin glass for an economically feasible design. Lastly, the conclusion of the economic aspect of thin glass is presented.

## 10.1. Development Dutch Horticultural Sector

In the Dutch horticulture sector, a trend of development and growth can been distinguished over the last years. The average arable area per greenhouse is expanding, while the yield and profit are increasing rapidly the last years, as can be seen in Figure 10.1. Figures 10.2 and 10.3 show the subdivision of the yield and costs in different topics. The average yield per greenhouse horticulture company increased mainly due to rising yields from the sale of flower and plants, while yields from vegetables and energy decreased. Overall, the yield for an average greenhouse farm increased in 2016 with 5.5% to € 2.2 million (Wageningen University & Research, 2017).

The total yield can be subdivided in three different topics, as shown in Figure 10.2:

- Product: the yield of the crop that is grown in the greenhouse, for instance vegetables, flowers or plants. This is the largest share of the total yield.
- Energy: the energy revenue is the yield that is achieved by selling and trading energy. However, the share of energy yields in average horticulture is not really high with 4-5% of the total yield.
- Other: yields that have an other source than the product or energy, such as grants.

The total costs can be subdivided in six different topics, as shown in Figure 10.3

- Labor: costs of both paid work and calculated labor for unpaid manpower.
- Starting material: costs for seed and propagating material.
- Energy: costs of energy, including services, taxes and motor fuel.
- Calculated interest rate: the interest rate is calculated against the market value of the relevant year. As a result, it is possible that the costs are lower than the interest paid.
- Write-off: the depreciation of the durable production materials.
- Other: costs that do not fit in the above-mentioned topics such as premium payments for the insurance.

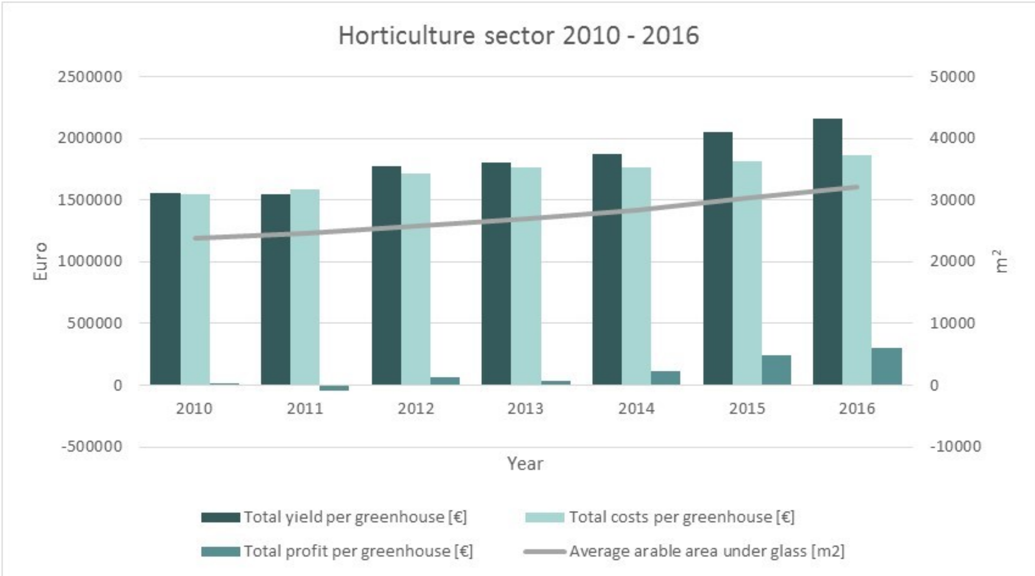



**Figure 10.1:** Development of yield, profit and costs in the horticultural sector between 2010 and 2016 (Wageningen University & Research, 2017)

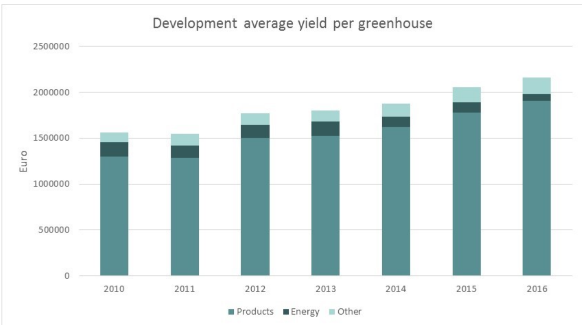



**Figure 10.2:** Development of the average yield per greenhouse in the horticultural sector between 2010 and 2016 (Wageningen University & Research, 2017)

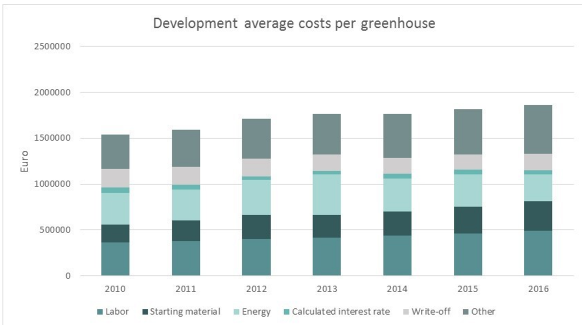



**Figure 10.3:** Development of the average costs per greenhouse in the horticultural sector between 2010 and 2016 (Wageningen University & Research, 2017)

## 10.2. Qualitative Comparison

In general, a commercial grower wants that the covering material provides optimal production at low costs. For implementation of a new covering material, it is therefore important that the increased yield outweighs the higher initial costs.

The Venlo system is the most common type greenhouse in the Netherlands and has been extensively developed to achieve the highest possible efficiency. Construction costs are minimized and the production systems are fully adapted. This means that is is difficult for a new type of greenhouse structure to compete with a Venlo system, because this new system has not yet been fully developed. This is why the choice is made to perform a qualitative comparison between the costs and benefits of the application of thin glass instead of regular float glass in greenhouse coverings, instead of a quantitative comparison.

### 10.2.1. Reference Greenhouse System

The most efficient greenhouses are achieved by establishing a combination of many different systems and expertises, as explained in Chapter 5. The costs of a greenhouse are therefore dependent on all of these individual components. However, the research in this report is focussed on the greenhouse covering, as explained in Chapter 6, and thus the costs for the comparison in this chapter will only be related to this part of the greenhouse system.

#### Costs

A subdivision of the costs for the reference greenhouse system needs to be made, before a comparison between the application of different covering materials can be made. The subdivision is based on the research set-up and is mainly based on the structural aspects of the greenhouse instead of the energy and crop aspects as treated in the previous section. The cost topics that can be distinguished are: building materials, production, transportation, construction, maintenance and insurance.

#### Yield

The profit for the reference greenhouse system can be divided in two topics for this research. The first topic is the profit for the greenhouse by the crop yield. The second topic is the energy yield by selling and trading of left-over energy.

### 10.2.2. Thin vs. Regular Glass

The qualitative comparison between the use of thin glass instead of regular glass will be based on the previous mentioned costs and yield topics. However, for the qualitative comparison between thin and regular float glass it is important to get an overview of both the advantages and disadvantages of using thin glass instead of regular float glass.

#### Advantages Thin Glass

Chemically treated thin aluminosilicate glass has five main advantages when compared to regular float glass:

- **Lightweight:** Weight saving often saves costs and results in a decreased environmental impact, because a smaller supporting structure can be used for a lighter covering material. However, a lighter material will also reduce costs during transportation and construction, because the panels are easier to handle by less persons.
- **Toughness:** Higher toughness can result in an increased impact resistance, however this still has to be researched as explained in Chapter 8. An increased impact resistance will result in less damage from hail storms and thus will also ensure lower insurance premiums and reparation costs.
- **Optical qualities:** Better optical qualities result in a 2% increase of the hemispherical light transmittance as explained in Chapter 7. In greenhouses the general rule applies that 1% more light will lead to 1% more yield and thus the increased optical qualities will lead to an increased yield.[1]
- **Weather resistance:** Increased weather resistance will elongate the life time of the covering material before it needs to be replaced. This results in the fact that it will take longer before the material properties will decrease when compared to the newly installed panels.
- **Bending resistance:** Increased bending resistance leads to a more flexible system in which the covering material will break less rapidly due to increased or unexpected loads. It also makes it easier to implement curved or dynamic systems without the necessity of hot bending of glass.

#### Disadvantages Thin Glass

Chemically treated thin glass has three main disadvantages when compared to regular float glass:

- **Initial costs:** Chemically strengthened thin glass is not yet widely used in the construction industry. The initial costs of $1m^2$ thin glass are higher than that of regular float glass, due to its more expensive treatment and the smaller supply for the construction industry.

[1] In addition to the properties of the covering material itself, the physical structure of the greenhouse is an element of consideration. The light transmittance results of Chapter 7 show that the transmission of thin glass only is a few percent when compared to the regular float glass. In this case, it becomes relevant to look at the extent of the light blocking by the physical structure. Often the light blocking by the supporting structure is about 10% (Broersma et al., 2011). An promising direction for optimisation of greenhouse design is minimizing the shading effect of the materials that are not letting through light. In fact, the combination of covering material and associated structural system should be considered to get a good overview of the transparency of the greenhouse.

- **Flexibility:** Thin glass panels need to be stiffened before they can be used as flat panels in the Venlo system, as explained in Chapter 9. The stiffening measures need to be prepared in the factory or at site which increases the production and/or construction time, but will also result in higher costs.
- **Structural properties:** The exact structural properties of thin chemically strengthened glass are not yet known. Thin glass panels need to be experimentally tested to prove that the structural properties of thin chemically strengthened aluminosilicate glass are indeed much higher than the properties of regular float glass, as explained in Chapter 8. The lack of experiments results in the fact that a very low design value needs to be used to ensure a safe design when using thin glass. Which results in the fact that not the full potential of the building material can be used at this moment.

### Comparison

The qualitative comparison is executed by comparing the previously determined topics for costs and yield for both regular float glass and thin glass. An estimation is made if the costs and yield are high, average or low for each of the topics for both regular float glass and thin chemically strengthened aluminosilicate glass. The previously mentioned advantages and disadvantages of using thin glass in a greenhouse covering design are hereby taken into consideration. An overview of the qualitative comparison of thin and regular float glass for application in greenhouse covering is presented in Figure 10.4.

| | Costs | Regular Float Glass | | Thin Glass | |
|---|---|---|---|---|---|
| Costs | Building materials | - | Float glass is produced on mass scale and is therefore cheap (≈ 2.5 €/m2) | + | Higher initial costs thin glass due to the smaller supply for construction industry (≈ 12-14 €/m2)<br>A stiffening solution is necessary and these material costs should also be added |
| | Production | - | Standardised dimensions and profiles are used | + | Special structure or adaptation of current structure is necessary for the stiffening of the panels<br>Chemical strengthening process is more expensive than the no treatment or heat strengthening |
| | Transportation | 0 | Regular sized trucks and materials need to be used | - | More panels can be put on one transport, because they are thinner and lighter |
| | Construction | 0 | Panels are heavy to handle by one person (≈ 27.1 kg)<br>Fast slide and fix system can be used | 0 | Panels can be handled by one person (≈ 3.69 kg)<br>Changes should be made to current structure. |
| | Maintenance | + | Special profiles are needed for reparation of a damaged panel | - | Flexibility of panels makes it easier to insert new panels<br>High optical quality so need to be cleaned less often |
| | Insurance | + | High damage risk for hail, so high premiums for insurance | - | Decreased premium because of reduced the hail damage risk due to increased impact strength |
| | | | ***Total: average cost*** | | ***Total: low cost, but largely depending on the initial costs of the thin glass*** |
| | **Yield** | | | | |
| Yield | Crop yield | + | System is optimised for highest crop yield possible | + | Higher light transmittance of 1-2%, so higher yield (according to the general rule-of-thumb)<br>Required structures for stiffening of the panel might block light |
| | Energy yield | 0 | Similar U-value<br>Insulating panels are heavy and need an adapted structure | 0 | Similar U-value<br>Lightweight insulating panels are possible that fit in the current used system |
| | | | ***Total: high yield, because system is optimised for highest yield*** | | ***Total: high yield, when taking into account future possibilities for insulating panels*** |

**Legend**

| | |
|---|---|
| + | High costs/yield |
| 0 | Average costs/yield |
| - | Low costs/yield |

**Figure 10.4:** Comparison regular float glass and thin glass for the application in greenhouse coverings

The following conclusions can be drawn from the qualitative comparison:

- The costs for a system with regular float glass are average. The building materials and production are low cost, because standardised sizes and profiles are used. However, the maintenance and insurance lead to higher costs due to an increased risk for hail damage.
- The costs for a system with thin glass are low, when the costs of thin glass decrease. The costs for transportation, construction, maintenance and insurance are low due to the low weight and high strength of the glass. However, the production and material costs are high. The total costs for this application are therefore mainly depending on the material costs.
- The yield is high for both applications. The crop yield will be higher for the thin glass application due to the slightly better light transmittance. When looking at insulating panels, the yield of thin glass will be higher due to its better light transmittance and similar insulating properties.

## 10.3. Economic Feasibility Study

The qualitative comparison in the previous section shows that the economic feasibility of the application of thin glass in greenhouse coverings is highly depending on the costs of the building materials. Therefore, the choice is made to perform a short study to investigate the influence of the costs of the material on the economic feasibility. The study will be simplified due to the lack of economic data for all of the individual parts of the greenhouse. The study therefore only includes the costs of the glass versus the crop yield.

### 10.3.1. Costs and Yield Thin Glass Application

Uncoated regular float glass costs approximately 2.5 €/$m^2$, while the costs for uncoated thin glass are approximately 13 €/$m^2$ (source: presentation AGC). The average area of a greenhouse in the Netherlands in 2016 was 32,200 $m^2$ (Wageningen University & Research, 2017). Which means that the initial extra costs for using thin glass in an average greenhouse are:

Additional costs thin glass = difference costs * average area greenhouse
Additional costs thin glass = (13-2.5) * 32,200 = € 335,100

The additional costs need to be compensated by lower costs for transportation and insurance and/or a higher yield. For the feasibility study only the material costs and crop yield will be studied, as explained previously, and thus the lower costs for transportation and insurance are not taken into account. The yield of an average greenhouse in the Netherlands in 2016 was approximately € 2,160,000. The yield for thin glass covering will be higher when compared to a regular float glass covering, due to the increased light transmittance, as shown in Chapter 7. The increased light transmittance of uncoated thin glass compared to uncoated regular float glass is approximately 2%, see Table 7.1. The general rule-of-thumb in greenhouse industry is that "1% less light in a greenhouse, is 1% less production or yield". If you reverse this rule, it can be said that in general 1% more light in a greenhouse will results in 1% more yield. This rule-of-thumb is used for the determination of the yield increase by applying thin glass:

Increased yield thin glass = percentage increased light transmittance * average yield
Increased yield thin glass = 0.02 * 2,160,000 = € 43,200

The costs for the thin glass application are higher than the yield and therefore it can be stated that this is not an economic feasible solution with the current price of thin glass. The costs of thin glass are relatively high due to smaller supply for the building industry. However, the market forces will ensure that the price of thin glass will drop as soon as the supply increases due to a higher demand from the building industry.

### 10.3.2. Maximum Costs for Feasibility

A short investigation will be performed in this section to research which price thin glass should have to result in an economically feasible design. The choice was made to only use the initial costs and crop yield for the feasibility study. Therefore, it can be stated that the increased yield needs to be higher than the additional initial costs for an economically feasible solution for thin glass. The following statement should be fulfilled for an economically feasible design:

$$\text{Feasible solution thin glass} \Rightarrow \text{additional costs} < \text{increased yield}$$

First the increased yield per $m^2$ greenhouse needs to be calculated:

$$\text{Increased yield per } m^2 = \text{increased yield per greenhouse / average area greenhouse}$$
$$\text{Increased yield} = € \, 43{,}200 \, / \, 32{,}200 \, m^2 = 1.34 \, €/m^2$$

A feasible solution for thin glass will thus be reached when:

$$\text{Additional costs} < 1.34 \, €/m^2$$

This means that the maximum allowed costs for thin glass for a economically feasible design is:

$$\text{Max. allowed costs thin glass} = \text{costs regular float glass} + \text{max. allowed additional costs}$$
$$\text{Max. allowed costs thin glass} = 2.5 + 1.34 = 3.84 \, €/m^2.$$

According to the feasibility study, the application of thin glass in greenhouse coverings will be economically feasible when the costs of thin glass panels drop to 3.84 $€/m^2$. However, the additional benefits of the application of thin glass, such as easier transportation/construction and less hail damage, are not taken into account for this study. The maximum price of thin glass can therefore be somewhat higher than the calculated 3.84 $€/m^2$ for maintaining an economically feasible design. However, it is advised to execute a more detailed study on the costs and benefits to get an insight of the total economic feasibility of thin glass in greenhouse coverings.

## 10.4. Conclusion

The research to the economic aspects of the application of thin chemically strengthened aluminosilicate glass results in the following conclusions:

- The costs for a greenhouse system with thin chemically strengthened aluminosilicate glass is mainly depending on the material costs of the thin glass.
- The costs for the transportation, construction, maintenance and insurance are lower for the application of thin glass compared to regular float glass, because of the low weight, high toughness, increased optical qualities and better weather and bending resistance of thin glass.
- A high yield can be achieved for both the application of regular float glass and thin glass. The crop yield will be slightly higher for thin glass application because of the better light transmittance, but the insulating properties of a single layer of thin glass are comparable to regular float glass and will result in a similar energy yield.
- At this moment thin glass is not yet economically feasible for the application in a single layer greenhouse covering due to its high material costs. However, it might be possible to make an economically feasible design for single layer thin glass panels for application in greenhouse coverings when the price of thin glass drops sufficiently due to a higher demand.
- The application of thin glass in insulating glass units (IGU) for the greenhouse covering results in stiffer panels with a higher energy yield when compared to single glass. The thin glass IGU will lead to lower costs due to the reduced weight, better optical qualities and higher toughness when compared to a regular float glass IGU. It is therefore advised to apply thin chemically strengthened aluminosilicate glass in IGU panels in order to achieve a greenhouse covering with better structural, energy and light transmittance properties, while having a solution that is economically attractive for greenhouse owners.

# 11

# Final Design

The numerical and experimental research performed in Chapter 9 provided a better insight in the behaviour of thin glass panels and various stiffening possibilities. The results of the structural behaviour study showed that the IGU panel is the best variant for stiffening a thin glass panel for application in greenhouse coverings. It was also concluded that the FE model for the IGU variant is accurate and can be used to predict the behaviour of a thin glass IGU panel under an evenly distributed load. The structural behaviour study was performed on panels that are smaller than the panels that are used in the reference Venlo system.

In this chapter the design for a full scale panel for application in the reference Venlo system is presented. Firstly, some general info about the design of IGU panels is presented. Secondly, an overview of the design of the panel is presented and the structural behaviour is studied by a numerical analysis. Hereafter, the building physics properties are evaluated.

## 11.1. General

Insulating glass units (IGU) typically consist of multiple glass panes that are sealed and held together structurally along their perimeters. The hermetically sealed interpane space is typically filled with an inert gas, such as argon or krypton, to improve the insulating value. The key function of the edge seal is to keep the glass panes separated at a certain distance and providing a barrier to prevent infiltration of water and keeping the gas inside the panel.

The edge seal consist of a number of components, such as a spacer bar, a desiccant and a sealant. However, these components are often combined and may each serve more than one purpose. An overview of an edge seal geometry is shown in Figure 11.1. Typically, the total width of the edge seal (s) varies from 8 to 12 mm. The interpane spacing thickness ($t_i$) is depending on several factors such as the number of glass panes and the gas filling. However, commercial edge seal thicknesses of 6 to 24 mm are common.

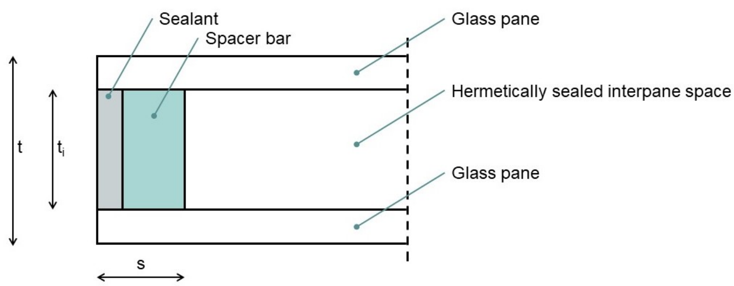



**Figure 11.1:** Visualisation of typical geometry IGU

The hermetically sealed interpane space ensures a structural cooperation between the two panes when externally loaded. This behaviour is researched in Chapter 9. The cooperation of the panel under a short-term load is assumed to be 100% and the external load will thus be divided evenly over the two panes, see Figure 11.2.

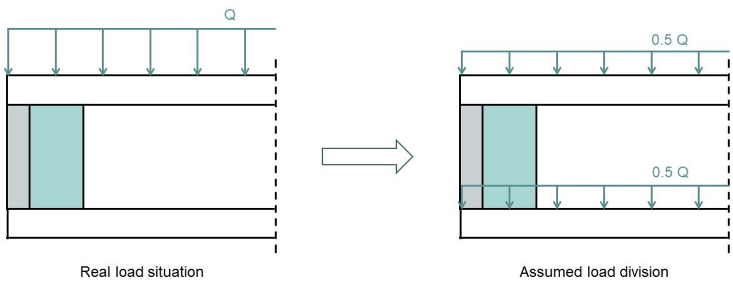



**Figure 11.2:** Left: real load situation of IGU under an external load. Right: assumed load situation of IGU by cooperation panels due to hermetically sealed air layer

## 11.2. Structural Behaviour

It is necessary to research the structural behaviour of the full scale IGU panel in order to check the structural integrity. The two criteria that must be fulfilled are:

- The in-plane displacements may not exceed the supporting distance of the aluminium frame:
  dTX < 5 mm and dTY < 5 mm
- The out-of-plane displacement of one panel relative to the other panel may not exceed $t_i$:
  dTZ < 15 mm

### 11.2.1. Input Numerical Analysis

There are slight changes in the input data of the full-scale FE models compared to the models used for the variation study in Chapter 9. The input data used in Chapter 9 is shown in Table 9.2 and Figure 9.2. The changes made to this input data for the structural design research are presented in this section.

#### Geometry and Loads

The used geometry is related to the standard dimensions of the Venlo system as shown in the reference system in Chapter 6. An overview of the geometry is presented in Figure 11.3.

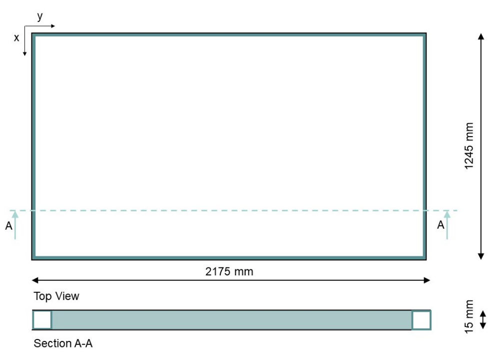



**Figure 11.3:** Geometry of full scale IGU panel

The general used dimensions for the glass panels are:

- Width glass = 1,245 mm

- Length glass = 2,175 mm
- Thickness glass = 0.55 mm
- Interpane spacing width = 15 mm

The applied loads and materials are the same as the applied loads for the reference model in the structural behaviour research (Chapter 9). However, the load is distributed over the top and bottom panel as explained previously. Only the load combination of permanent load with wind load is checked, because this is the governing load combination as explained in Chapter 9.

A fine mesh width of 20 mm is used to get accurate results. The permanent load is applied in 10 load-steps of 10% of the total permanent load. The wind load is applied in 100 load-steps of 1% of the total wind load.

#### Boundary Conditions

In the previous chapter non-tension supporting conditions are used, however in a greenhouse system the upwards movement of panels is prevented by the aluminium system. To simulate this behaviour, the choice is made to use supporting conditions in which the translation in z direction is fixed in both positive and negative direction.

#### Analysis

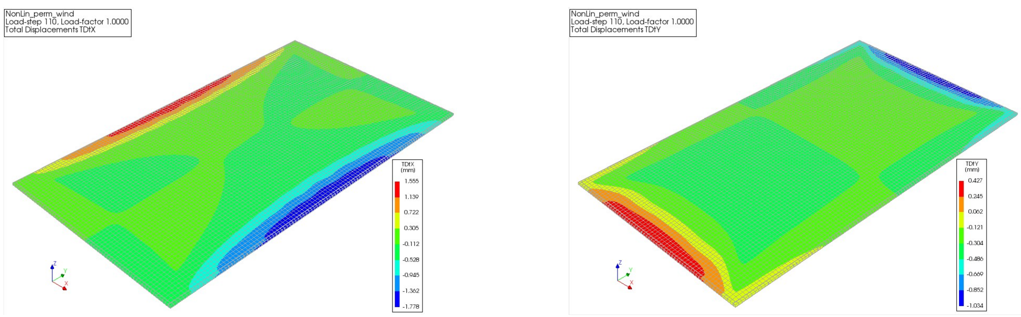
The general rule is that a linear analysis can be performed when the deformation is smaller than half of the thickness ($w < t/2$). The assumption is made that the deformations of the glass plate will be larger ($w > t/2$) and this is why there is chosen to perform a geometrical non-linear analysis.

### 11.2.2. Results Numerical Analysis

The results of the numerical analysis performed in DIANA are presented in this section.

#### In-plane Deformations

The in-plane deformations after the application of the wind load are presented in Figures 11.4a and 11.4b. The maximum in-plane deformations are resp. -1.778 mm and -1.034 mm in X and Y direction. The previously set in-plane deformation limit, related to the supporting width, is 5 mm. The maximum in-plane deformations are smaller than the limit and therefore it is concluded that the panel will not fall out of the aluminium system due to the wind load.



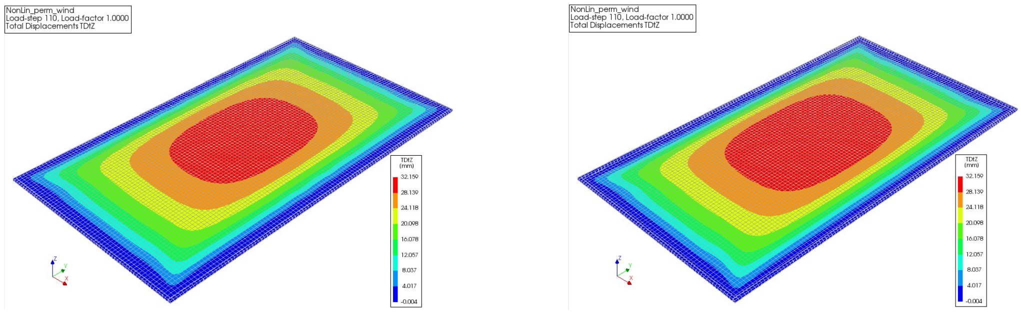

**(a)** max. dTX = -1.778 mm

**(b)** max. dTY = -1.034 mm

**Figure 11.4:** In-plane deformation results numerical analysis

#### Out-of-plane Deformations

The out-of-plane deformations after the application of the wind load are presented in Figures 11.5a and 11.5b. The maximum out-of-plane deformation for both top and bottom panel is 32.159 mm in Z direction. The maximum relative displacement between the panels is therefore 0 mm. The previously set out-of-plane deformation limit, related to the interpane spacing thickness, is 15 mm. The maximum relative out-of-plane deformations are smaller than the limit. Therefore it is concluded that the top and bottom panel will move together and do not touch each other.




**(a)** max. dTZ top panel = 32.159 mm

**(b)** max. dTZ bottom panel = 32.159 mm

**Figure 11.5:** Out-of-plane deformation results numerical analysis

### Stresses

The principal stresses in the panels after the application of the wind load are presented in Figure 11.6. The maximum principal stresses are exceeded the previously set characteristic bending tensile strength of 260 MPa. However, it can be seen that the largest stresses are present at the edges where the edge seal is connected to the panels. An infinite stiff connection is assumed for the FE model, but in reality these connections will have a lower stiffness due to elasticity of the glue etc. It is therefore not possible to draw the right conclusions on the stresses present in the thin glass panels. This is why the advise is given to perform further research to the stresses in these connections when this configuration is applied for a greenhouse covering panel.

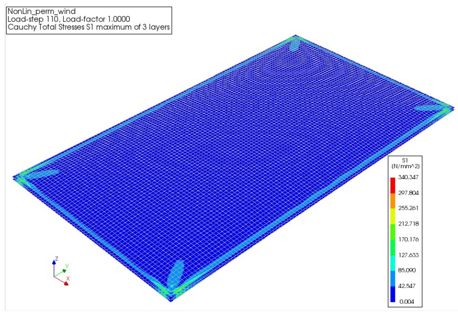



**Figure 11.6:** Maximum principal stresses S1 in panels = 340.347 N/mm$^2$

## 11.3. Building Physics

Not only the structural behaviour but also the building physics properties of the full scale panel are important for the greenhouse design. The two examined building physics criteria are: light transmittance and thermal transmittance.

### 11.3.1. Light Transmittance

The light transmittance is important for the crop growth in the greenhouse. The use of two layers of glass reduces the light transmittance when compared to nowadays used single layer of float glass. The hemispherical light transmittance of the full scale panel is assumed to be the same as the double configuration of 0.55 mm Leoflex that is tested by the WUR, see Chapter 7.

The light transmittance properties of the full scale panel are:

$$\text{Hemispherical light transmittance} = 75.3\%$$

Perpendicular light transmittance = 84.5%

### 11.3.2. Thermal Transmittance

The thermal transmittance of the full scale panel can be calculated according to the NEN-EN 673, as explained in Chapter 7.

The resulting values for thermal transmittance of the full scale panel are shown in Table 11.1.

**Table 11.1:** Results of thermal transmittance full scale thin glass IGU panel design

| **Gas filling interlayer** | **U-value** [$W/m^2K$] |
|---|---|
| Air | 3.1 |
| Argon | 2.9 |

### 11.3.3. Fulfilment Requirements

The requirements of the building physics properties for a greenhouse with a covering of a single layer float glass are stated by TNO and are presented in Chapter 5. An overview of the required values, comparing values of an IGU panel with float glass and the final values of the full scale design of an IGU panel with thin glass are presented in Table 11.2.

**Table 11.2:** Fulfilment building physics requirements for greenhouse covering design

| | **Requirement TNO** | **IGU extra clear float glass** | **Full scale design IGU thin glass** |
|---|---|---|---|
| Perpendicular light transmittance | >90% | 84.2% | 84.5% |
| Hemispherical light transmittance | >82% | 74.7% | 75.3% |
| U-value | <7.5 $W/m^2K$ | 3.0 $W/m^2K$ | 3.1 $W/m^2K$ |

The comparison in Table 11.2shows that the light transmittance values of the full scale design do not fulfil the requirements of TNO for a greenhouse covering of a single layer of float glass. However, the light transmittance properties of the full scale design are better than that of an IGU with float glass. The insulation value of the full scale design is lower than the stated value by TNO and are comparable to the insulating properties of an IGU with float glass. It can be concluded that the building physics properties of the full scale IGU panel with thin glass are similar to that of an IGU that consist of float glass.

# PART IV

## Final Remarks

# 12 Conclusions

The objective of the research was to determine the applicability of thin chemically strengthened aluminosilicate glass in greenhouse coverings, by taking into account the light transmittance, structural properties, structural behaviour and economics. In this chapter, the conclusions of the research are presented. Firstly, the general conclusions regarding the four research topics are presented. Hereafter, answers to the sub research questions, as presented in Chapter 3, are provided. The answering of the sub-questions will subsequently lead to the answering of the main research question.

## 12.1. General

The research to the applicability of thin glass in greenhouse coverings is subdivided in four research topics: building physics, structural properties, structural behaviour and economics. The general conclusions for each of these individual topics are presented in this section.

### Building Physics

- The hemispherical light transmission of uncoated thin glass is 84% and is higher than the set lower limit of 82% for greenhouse design. A single layer of thin glass can thus be used as greenhouse covering material without negatively influencing the light transmittance.
- The application of uncoated thin glass, compared to uncoated float glass, results in an increased hemispherical light transmission of 2% and subsequently an increased yield of 2%.
- The research to the light transmittance of different coatings for thin glass is still ongoing and additional experiments still need to be performed at the WUR. Based on the calculations performed by the WUR, it can be expected that coated thin glass will result in an increased hemispherical light transmittance when compared to coated float glass. However, more experiments have to be performed on thin coated glass to draw detailed conclusions on the effect of coating thin glass compared to float glass.
- The research to the insulating properties shows that double glazing has a lower U-value and therefore better insulating properties than a single glass panel. Filling the cavity in double glazing units with Argon instead of air results in a lower U-value and therefore has better insulating properties.
- The thin glass IGU configurations have higher U-values than the regular float glass IGU panels. However, the difference is small and therefore it can be concluded that the insulating properties of thin glass in insulated glass units is comparable to the insulating properties of insulating glass units of regular float glass.

### Structural Properties

- The strength of glass is very high, when looking at the atomic level. However, the strength of glass is reduced by flaws in the glass surface and edges.

- Safety is an important factor when designing (greenhouse) structures that include glass. The broad range in material quality results in a large spread of tensile strength tests. This is why the characteristic values are relatively low. The design values will even be lower due to the necessity of using a material safety factor to determine a safe design value.
- Various testing procedures are presented in the Dutch design standards for the determination of the bending strength of glass. However, the Dutch design standards are developed for regular float glass and can not be directly applied for thin chemically strengthened aluminosilicate glass.
- The characteristic bending tensile strength of thin chemically strengthened aluminosilicate glass is set to 260 MPa for this research. However, the bending strength of thin glass is not yet extensively researched. The research of Neugebauer (2016) showed that the "bending with constant radius with influence of edge strength" is the most promising testing method for thin glass. This test method should be further investigated relating to its applicability for thin glass.
- The impact strength of thin glass is likely to be higher than that of regular float glass due to the chemical strengthening treatment. However, no specific value could be determined due to a lack of data.
- At this moment almost no data is available on the quantity, recurrence intervals, size, speed etc. of hailstorms in the Netherlands. Further hail research requires good hail data, which can be obtained by using the traditional hailpads or use more advanced measurement systems such as radar or pressure sensitive plates.

### Structural Behaviour

- The results of the FE models are in general comparable to the results of the experiments. Therefore it is concluded that the FE models are built-up correctly and can be used for the prediction of the behaviour of flat thin glass panels. However, out-of-plane buckling behaviour for large deformations is visible during the experiments, but is not present in the FE models.
- The in-plane deformations in the x and y direction of a non stiffened thin glass panel in the reference system are exceeding the maximum values allowed according to the Dutch design standards. The maximum values are based on the supporting width of aluminium greenhouse systems. Exceeding these values may cause the panel to fall out of the aluminium supporting system. Stiffening of the thin glass panels is necessary to decrease the deformations of the panel due to an evenly distributed load.
- Changing supports to fixed supports decreases the deformations in x, y and z direction, but the experiment showed that it is hard to realise fully fixed conditions in practice. Adjustments in the boundary conditions have a large influence on the behaviour of the plate. Small changes in these conditions will result in relative big differences in the behaviour of the plate.
- The sandwich structure has the lowest deflections and this suggests that this variant is the best way to stiffen a thin glass panel. However, the IGU structure also has a high stiffness, but without the necessity of light blocking spacers in the middle of the plate. For the feasibility of the greenhouse design the increase of the incident light is more important than the deflection in z direction. The deformations of the IGU panel are slightly larger than the sandwich panels, but the IGU panel has a higher light transmittance because no light blocking elements are necessary. Therefore it is concluded that the use of an IGU system with a hermetically sealed air layer is the best way to stiffen a thin chemically strengthened aluminosilicate panel for the use in greenhouse coverings.

### Economics

- The costs for a greenhouse system with thin chemically strengthened aluminosilicate glass is mainly depending on the high material costs of thin glass. However, the costs for the transportation, construction, maintenance and insurance are lower for the application of thin glass compared to regular float glass, because of the low weight, high toughness, increased optical qualities and better weather and bending resistance of thin glass.
- A high yield can be achieved for both the application of regular float glass and thin glass. The crop yield will be slightly higher for thin glass application because of the better light transmittance, but the insulating properties of a single layer of thin glass are comparable to regular float glass and will result in a similar energy yield.
- Thin glass is not yet economically feasible for the application in a single layer greenhouse covering due to the high material costs. However, it might be possible to achieve an economically feasible design for single layer thin glass panels for application in greenhouse coverings when the price of thin glass drops

sufficiently due to a higher demand.

- The application of thin glass in insulating glass units (IGU) for the greenhouse covering results in stiffer panels with a higher energy yield when compared to single glass. The thin glass IGU will lead to lower costs due to the reduced weight, better optical qualities and higher toughness when compared to a regular float glass IGU. It is therefore advised to apply thin chemically strengthened aluminosilicate glass in IGU panels in order to achieve a greenhouse covering with better structural, energy and light transmittance properties, while having a solution that is economically attractive for greenhouse owners.

## 12.2. Answers to Research Questions

The research is shaped by the main research question and the complimentary sub-questions that are presented in Chapter 3. The sub-questions represent the different subjects that are treated during the research. Answering the sub-questions will ultimately lead to the answer to the main research question.

### Sub-Questions

*How does the application of thin chemically strengthened aluminosilicate glass influence the light transmittance and thermal transmittance of the greenhouse covering?*
The hemispherical light transmittance for a single panel of uncoated thin chemically strengthened aluminosilicate glass is 84%, while it is 82% for a single panel of uncoated regular float glass. The hemispherical light transmittance of uncoated thin glass is therefore 2% higher than that of regular float glass. However, it is not yet possible to draw conclusions about the light transmittance of coated thin chemically strengthened aluminosilicate glass and to compare it with regular float glass, because the research on uncoated thin glass panels is still ongoing and at this moment there are not sufficient test results available.

*What are the structural properties of thin chemically strengthened aluminosilicate glass?*
The two most important structural properties for thin glass application in greenhouse coverings are: bending strength and impact strength. The characteristic value for the bending tensile strength of thin chemically strengthened aluminosilicate glass is for this research set to 260 MPa. This value is based on the properties provided by the producer and the results of the first thin glass bending tests executed at the Delft University of Technology. However, the exact bending strength of thin glass panels needs to be determined more specifically in order to be able to use the thin glass to its full structural potential. The impact strength of thin chemically strengthened aluminosilicate panels is not further studied in this research and therefore no characteristic value for the impact strength of thin glass panels can be provided. However, based on previous research, it is concluded that the impact strength of thin glass panels is higher than that of regular float glass panel due to the chemical treatment.

*What is the structural behaviour of thin chemically strengthened aluminosilicate glass for different load cases when applied in greenhouse coverings?*
Large in-plane and out-of-plane displacements are present when non stiffened thin chemically strengthened aluminosilicate glass panels are applied in the reference system. The out-of-plane displacements are not likely to cause problems, because the thin chemically strengthened aluminosilicate glass panels have a high bending resistance. However, the large in-plane displacements in x and y direction can cause the panel to slip out of the aluminium supporting structure. It is necessary to stiffen flat thin chemically strengthened aluminosilicate glass panels for application in the Venlo systems in order to prevent the panel from falling out of the aluminium supporting structure when the maximum wind load is present.

*In which way can a thin chemically strengthened aluminosilicate glass panel be designed so that the structural integrity of the system is maintained during external loading?*
A flat panel can be stiffened by two different methods: the supports can be adjusted or the panel itself can be stiffened. The most promising solution resulting from the experimental and numerical research is a sandwich panel. However, the experimental and numerical research on the IGU structure also shows a high stiffness, but without the necessity of light blocking spacers in the middle of the plate. For the feasibility of the

greenhouse design the increase of the incident light is more important than the out-of-plane deflection. The deformations of the IGU panel are slightly larger than the sandwich panels, but the IGU panel has a higher light transmittance because no light blocking elements are necessary. Therefore it is concluded that the use of an IGU system with a hermetically sealed layer is the best way to stiffen a thin chemically strengthened aluminosilicate panel for the use in greenhouse coverings.

*Which economic benefits does the application of thin chemically strengthened aluminosilicate glass in greenhouse coverings have compared to the regular float glass?*
The material costs of thin chemically strengthened aluminosilicate glass are higher, but the transportation, construction, maintenance and insurance costs are likely to be lower due to the low weight, high toughness, increased optical qualities and better weather and bending resistance of thin glass. For a single layer of glass, the crop yield will be higher due to the increased light transmittance of uncoated thin glass. The application of thin glass in insulating glass units (IGU) for the greenhouse covering results in stiffer panels with a higher energy yield when compared to single glass. The thin glass IGU will lead to lower costs due to the reduced weight, better optical qualities and higher toughness when compared to a regular float glass IGU.

### Main Question

*Can thin chemically strengthened aluminosilicate glass be used to improve the properties of greenhouse coverings regarding the buildings physics, structural properties, structural behaviour and economics?*

Yes. Thin chemically strengthened aluminosilicate glass has a better light transmittance, higher bending strength and increased impact strength compared to regular float glass. This leads to an increased crop yield and lower costs for transportation, construction, maintenance and insurance which makes thin glass an attractive alternative for regular float glass. However, the material costs are very high at this moment and an economically feasible solution will only be possible when the price of thin glass decreases or when the crop and/or energy yield increase further.

The decreased thickness results in a lower stiffness of the glass panels. Therefore, it is necessary to stiffen a single panel of thin chemically strengthened aluminosilicate glass before it can be applied in the desired large spans. The research in this report is focussed on the stiffening of flat panels for application in the widely used Venlo systems. The best way to stiffen the flat thin glass panels for application in a Venlo system is by making an insulating glass panel in which the hermetically enclosed air layer provides additional stiffness without the need of additional light blocking spacer elements. It is therefore advised to apply thin chemically strengthened aluminosilicate glass in IGU panels in order to achieve a greenhouse covering with better structural, energy and light transmittance properties, while having a solution that is economically attractive for greenhouse owners.

However, the main advantages of thin chemically strengthened aluminosilicate glass, the flexibility and high bending resistance, are not utilized when it is applied in a flat configuration for the Venlo greenhouse systems. The development of a total new greenhouse concept, in which advantage is taken of the flexibility and high bending resistance, might result in a greenhouse design that has even better light transmittance properties than the nowadays widely used Venlo systems.

# 13 Recommendations

The subject of applying thin chemically strengthened aluminosilicate glass in greenhouse structures is relatively new and not a lot of knowledge was available during the start of the research. Greenhouse design is complex because of the different divisions that need to cooperate for an optimal greenhouse design. This is why the choice is made to define the scope of the research extensively at the beginning of the research. This resulted in a detailed definition of the greenhouse parameters that are studied in order to achieve a general overview of the applicability of thin chemically strengthened aluminosilicate glass for greenhouse coverings. The set scope and simplification of certain assumptions during the research lead to several recommendations for further research, which are presented in this chapter. Firstly, the general recommendations for further research on thin glass are treated. Hereafter, the recommendations for further research on the application of thin glass in greenhouses are presented.

## 13.1. Thin Glass General

- Firstly, it is recommended to perform into depth research of the bending strength of thin glass. The bending strength used in this research is based on the material properties presented by the producer. However, the first experiments that are conducted at the Delft University of Technology show that much higher bending stresses can be reached before failure occurs. It is necessary to perform more experiments for the determination of a realistic safe characteristic value for thin glass in order to be able to use thin glass to its full structural potential.
- Secondly, it is recommended to study the influence of edge and surface flaws and the (post) breakage behaviour of thin chemically strengthened aluminosilicate glass panels for the design of safe structures.
- Thirdly, it is recommended to look further into the impact strength of thin glass. This material property is unknown at this moment, while a better impact behaviour is expected for chemically treated glass. The determination of a characteristic value for the impact strength of thin chemically strengthened aluminosilicate panels is necessary when thin glass designs need to withstand impact loads such as hail.
- Lastly, it is advised to look further into the local buckling effect at the edges of a perpendicularly loaded thin chemically strengthened aluminosilicate panel. Out-of-plane buckling behaviour is observed during the experiments and might have a negative effect on the strength, stiffness, reflections and applicability of thin glass panels.

## 13.2. Thin Glass in Greenhouses

- Firstly, it is recommended to perform further research to the light transmittance of coated thin chemically strengthened aluminosilicate glass panels. At the time of this research, only results for the uncoated thin glass panels and predictions for coated thin glass panels were available. However, most glass panels used in Dutch greenhouses are coated for a better light scattering which is beneficial for the crop yield.

- Secondly, it is advised to look further into the vulnerability of thin chemically strengthened aluminosilicate panels to hail damage. It is expected that the chemical treatment increases the impact resistance. For a complete analysis of the possible reduction of hail damage by applying thin glass in greenhouses it is necessary to look at the impact behaviour of thin glass panels under hail load. However, at this moment there is a lack of hail data for the Netherlands and therefore it is also advised to look further into the collection of hail data for several locations in the Netherlands.
- Thirdly, it is strongly advised to perform large scale tests for stiffened flat thin glass panels. Small scale experiments were performed in this research to validate the FE models. However, the influence of the scale effect on the structural behaviour of the stiffened flat panel is not taken into account.
- Fourthly, it is suggested to perform a more detailed economic feasibility study for the application of thin glass in greenhouse coverings. A simplified economic feasibility study is performed in which only the material costs and crop yield are accounted for. However, the use of thin glass will also result in several other changes in costs and yields which should be taken into account in order to get a complete overview of the economic feasibility for the application of thin glass in greenhouse coverings.
- Lastly, it is advised to look into the application possibilities for thin glass in alternative greenhouse systems that differ from the Venlo system. For this research the choice was made to focus on the application of thin glass in a flat configuration for use in the Venlo system. However, it is concluded that it is necessary to stiffen thin glass panels for the application in a flat configuration and thus no advantage is taken of the main benefits of thin glass: the high bending resistance and flexibility. Curved thin glass panels will have a higher stiffness and less stiffening measurements will be necessary. Hence, it will be interesting to explore the possibilities of using thin chemically strengthened aluminosilicate glass for arched greenhouses. Furthermore, research to the applicability of thin glass in dynamic greenhouse coverings for ventilation or adaptive stiffening methods might be promising.

# PART V

Appendices

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# A

# Leoflex Data Sheets

AGC Leoflex™ opens the door to new groundbreaking opportunities for glass. Leoflex™ is very thin, chemically strengthened aluminosilicate glass, offering higher strength compared to tempered soda lime. This results in new opportunities for designers to create thinner or curved designs, while maintaining the beauty of glass.

This next-generation glass presents additional benefits in the industrial and building environment: superior clarity without any green tint, flexibility as well as scratch resistance. Whether you are an architect, designer or builder or an industrial product manufacturer, you can now get the weight benefits of plastic sheets with the superior performance and durability of glass.

Leoflex™ is produced using AGC technology that ensures the highest quality product.

## Technical specifications

### LEOFLEX™

**Leoflex™ is the ideal solution for applications requiring very thin glass with high mechanical resistance.**

| | Clear float glass (with thermal tempering) | | Leoflex™ (with chemical tempering) | | | | |
|---|---|---|---|---|---|---|---|
| | 3 mm | 4 mm | 0.55 mm | 0.85 mm | 1.1 mm | 1.3 mm | 2 mm |
| Weight (kg/m²) | 7.5 | 10.0 | 1.4 | 2.1 | 2.7 | 3.2 | 5.0 |
| Max Compressive Strength (MPa) | max 150 | max 150 | > 800 | > 800 | > 800 | > 800 | > 800 |
| Compressive marginal stress (MPa) | 80 | 80 | 260 | 260 | 260 | 260 | 260 |
| Theoretical min radius curvature* (mm) | 1500 | 2000 | 90 | 130 | 170 | 200 | 400 |
| Vickers Hardness | 527 | 527 | 673 | 673 | 673 | 673 | 673 |
| Ug value EN 673 (W/m².C) | 5.79 | 5.76 | 5.87 | 5.86 | 5.85 | 5.84 | 5.82 |
| Light transmission EN 410 (D65.2°) LT % | 90.3 | 89.8 | 91.3 | 91 | 90.8 | 90.6 | 89.9 |
| Solar energy transmission EN 410 (D65.2°) TE % | 85.7 | 84.4 | 91.6 | 91.5 | 91.4 | 91.3 | 91 |
| Solar Factor EN 410 (D65.2° ) SF % | 87.5 | 84.9 | 91.7 | 91.6 | 91.5 | 91.4 | 91.2 |

(*) approx. value, depending on application

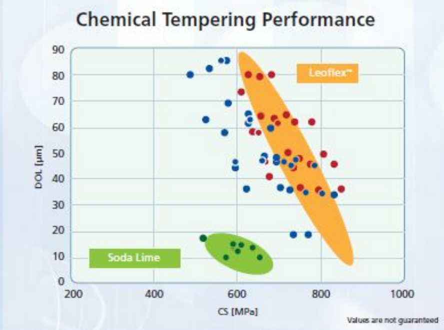
### Processing options

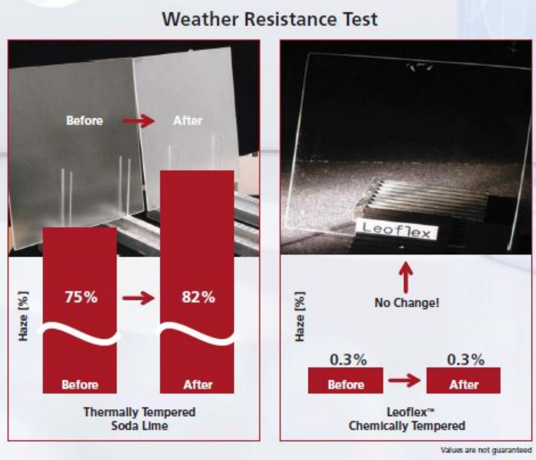
| | |
|---|---|
| Safety | Laminating (PVB or EVA), after chemical tempering |
| Cutting | Straight or circular, before and after chemical tempering |
| Shaping and edge finishing | Edge grinding (chamfering), before and after chemical tempering |
| | Grinding, before chemical tempering |
| | Drilling, before and after chemical tempering |
| Special treatments | Acid-etching, before and after chemical tempering |
| | Silk screen printing, after chemical tempering |
| | Painting and silvering, after chemical tempering |
| | Cold bending, after chemical tempering |
| Insulated glazing units | Double or triple glazing |

NOTE: Some glass treatments are subject to limitations and must be carried out in specific conditions. Please contact AGC for more information (see contact details at the back).

**Material Properties:**

| | Property | Measurement | Leoflex™ | Soda Lime |
|---|---|---|---|---|
| Mechanical | Density | g/cm$^3$ | **2.48** | 2.50 |
| | Young's Modulus | GPa | **74** | 73 |
| | Shear Modulus | GPa | **30** | 30 |
| | Poisson's Ration | | **0.23** | 0.21 |
| | Vickers Hardness | before CT | **595** | 533 |
| | Vickers Hardness | after CT | **673** | 580 |
| Thermal | CTE | [10$^{-7}$](50~200°C) | **98** | 85 |
| | Tg | °C | **604** | 550 |
| | Softening Point | °C | **831** | 733 |
| | Annealing Point | °C | **606** | 554 |
| | Strain Point | °C | **556** | 511 |
| Optical | Refaction Index | Nd | **1.51** | 1.52 |
| | Photoelastic Constant | nm/cm Mpa | **28.3** | 25.6 |
| Electrical | Volume Resistivity | log (Ω • cm) | **8.4** | 8.5 |


# B

# Topic exploration

This Appendix presents the research of the topic exploration that is treated in Chapter 2. The four topics that are explored in the sections below are based on the four options of stiffening a thin panel. The topics are, one by one, explored for its feasibility for further research. This exploration consists of a short literature overview and small research. The topic definition and conclusion of the exploration are presented in Chapter 2.

## B.1. Topic 1: Air-inflated Panels

This section treats first a short overview of theory related to air-inflated structures: synclastic surface and the membrane theory. Then the feasibility of the topic is treated in which the possible problems and the short research are presented.

### B.1.1. Theory Pneumatic Structure

No research is yet performed on the use of air pressure to stiffen thin glass panels. However, the application of air pressure to stiffen structures is already researched for membrane structures. The theory on membrane structures will form the theoretical background from where the feasibility of the topic will be explored.

A synclastic surface is a surface which has a positive Gaussian curvature at all points, this means that both curvatures are pointed in the same direction. The Gaussian curvature is defined as the product of the two principal curvatures of a surface in a point (Aanhaanen et al., 2008).

It is not possible to reach equilibrium of forces when two curvatures are present in the same direction, which is the case for a synclastic surface (see Figure B.1). A surface load has to be applied in order to reach equilibrium of forces and to have a stable structure. An air-inflated structure has a constant surface load (the air pressure) and consequently it will always have a synclastic shape.

### B.1.2. Exploration Potentials Topic

It is necessary to explore the potential of the application of thin glass in air-inflated panels in order to arrive at a conclusion for the feasibility of this application. The potentials will be explored by firstly defining the possible problems for the application of thin glass in air-inflated panels. Hereafter a simplified mechanical model will be composed and a couple of simplified analyses will be performed on this model in order to investigate the necessary air-pressure and occurring initial stresses in the glass. Finally, a conclusion will be drawn on the results of the exploration.

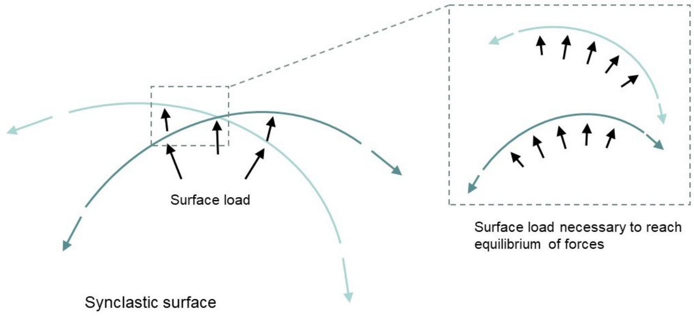



**Figure B.1:** Force distribution in a synclastic membrane

### Possible Problem

At this moment, no research has yet been performed on the application of thin glass panels in air-inflated structures. It is assumed that thin glass panels can be considered to fit into the description of the films that are used for conventional pneumatic structures. However, thin glass has not exactly the same material properties as the traditional films and this might cause problems for the application of thin glass for such structures. This is why there will be looked into three possible problems of applying thin glass in such structures in order to check if these problems are manageable or insuperable.

The first problem is that the Young's modulus (E) of thin glass is 65,000-75,000 $N/mm^2$, while the E for EFTE (widely used for membrane structures) is about 1,500 $N/mm^2$. The Young's modulus is a measure of stiffness of a material and determines the extensibility of the material. In general, a larger force is needed to deform a stiff material with a higher Young's modulus compared to a material with a lower Young's modulus. The use of thin glass, with a higher E-modulus, ensures that the air pressure in the panel should be larger compared to the use of a membrane material such as EFTE. The application of a larger air pressure might reduce the safety of the panels.

The second problem is the sealing of the thin glass panel. A constant air pressure should be applied between the two layers of glass and this requires an air tight connection between the two layers of glass. However, these connections should be able to account for a change of air pressure and the accompanying shape change of the glass panels.

The third problem is related to the double curving of the glass panels in order to arrive at the synclastic shape. The double curved shape of a glass panel introduces in-plane stresses that might be so large that the remaining strength is not sufficient to carry the loads.

### Short Research

The above explained problem of the initial stresses due to the double curving of the glass is chosen for further investigation and is the basis for the structural feasibility study with a Finite Element (FE) model. The program SJ Mepla is used for the creation and analysis of the FE model. The aim of the analysis is to investigate the initial tensile stresses in the glass when the pressure is increased and to see if the initial stresses reach the ultimate strength of the material.

A panel of 400 by 400 mm and a thickness of 0.8 mm is created in SJ Mepla. The plate is simply supported along the edges and a dead load and air pressure are applied. The air pressure is applied as a distributed load in negative z-direction and is varied in order to study the change in initial stresses when the air pressure is increased. The pressure in air-inflated membrane structures is around 0.001 $N/mm^2$ (Aanhaanen et al., 2008). This value is therefore taken as starting point for the distributed load that is applied in the FE model.

The general rule is that a linear analysis can be performed when the deformation is smaller than half of the thickness ($w < t/2$). The assumption is made that the deformations of the glass plate will be larger ($w > t/2$) and this is why there is chosen to perform a geometrical non-linear analysis.

The following material properties are used in the FE model, see Table B.1. These properties are based on the previously explained material properties of aluminosilicate glass.

**Table B.1:** Material properties used for mechanical model

| **Property** | | **Unit** |
|---|---|---|
| $E$ | 74,000 | $N/mm^2$ |
| $\nu$ | 0.23 | – |
| $\rho$ | 2.7337e-09 | $T/mm^3$ |
| $\alpha$ T | 1e-05 | $1/K$ |
| $\Delta$ T | 0 | $K$ |

The intermediate results of the analysis are shown in Figures B.2 and B.3 and diagrams B.4 and B.5. It can be seen that the initial stresses increase when the pressure is increased, this is as expected. The stresses in the corners are higher than the stresses in the middle of the plate, this is also as expected. The tensile strength of fully tempered glass is showed in diagram 1 (80 $N/mm^2$), because of the fact that the tensile strength of thin glass is not yet determined. The tensile strength of fully tempered glass is reached when the pressure is increased to 0.003 $N/mm^2$ at this moment the deflection of the plate is about 9 mm in z-direction. The deformation of 9 mm is likely to be not sufficient to provide sufficient stiffness to the external loads such as wind load. A higher pressure is needed in order to deform the sheets so much that they provide enough stiffness, only then the initial tensile stresses in the glass will already be very large. Therefore it can be concluded that, based on the material properties, glass is not a good material to use in an air-inflated cushion.

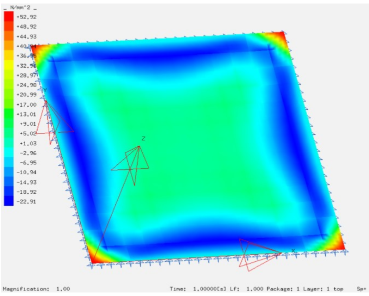


**Figure B.2:** Stresses Sp+ $[N/mm^2]$

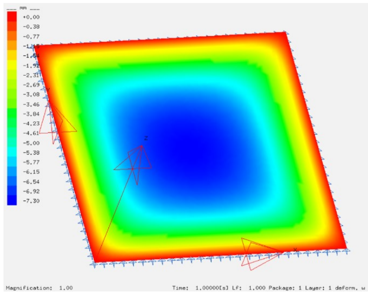


**Figure B.3:** Deformations w $[mm]$

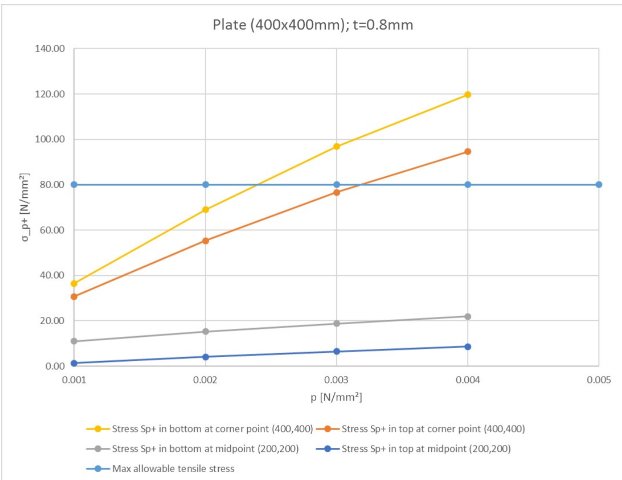



**Figure B.4:** Results stresses Mepla analysis plate 400 x 400 mm and t=0.8 mm

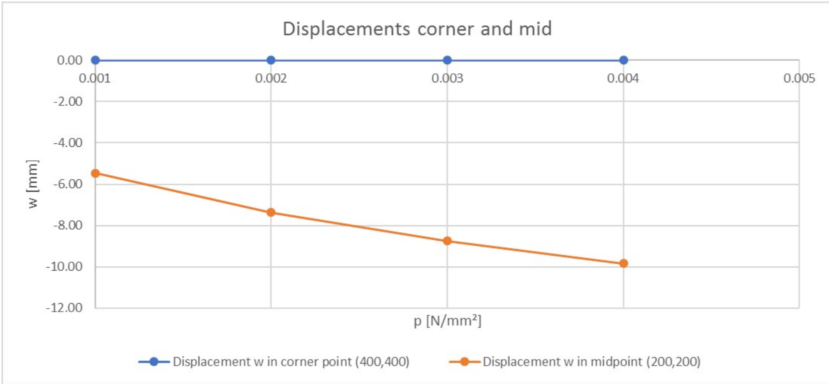



**Figure B.5:** Results displacements Mepla analysis plate 400 x 400 mm and t=0.8 mm

## B.2. Topic 2: Twisted Panels

This section treats first a short overview of theory relevant for twisted thin glass panels: twisting of float glass and cylindrical bending of thin glass. Then the feasibility of the topic is treated in which the possible problems and the short research are presented.

### B.2.1. Theory Cold Bended Glass

Several researches are carried out on the behaviour of cold twisted float glass. No research is yet carried out to the behaviour of cold twisted thin glass panels, but Simoen (2016) has carried out research on the cylindrical cold bending of thin glass. The results of relevant researches are presented in the following section and will form the theoretical background on which the feasibility of the topic will be explored.

#### Cylindrical Float Glass

The simplest forms that can be obtained through cold bending are single-curvature developable surfaces (part of a cylinder). The cylindrical curved glass plate has a constant curvature, with a radius R. The cold bending of a plate in a cylindrical shape introduces bending moments that result in bending stresses. The resulting bending stresses are permanently present in the glass and reduce the capacity of the glass plate to withstand external loading. The bending moments can be calculated with equation B.1.

$$M = \frac{EI}{R} \tag{B.1}$$

In which $E$ is the Young's Modulus in $N/mm^2$, $I$ is the moment of inertia in $mm^4$ and $R$ is the bending radius in $mm$.

The maximum bending stress can be calculated with equation B.2.

$$\sigma = \frac{Mt}{2I} \tag{B.2}$$

In which $M$ is the bending moment in $Nmm^2$ and $t$ is the thickness in $mm$.

Combining equation B.1 and B.2 results in:

$$\sigma = \frac{Et}{2R} \tag{B.3}$$

The stress from equation should never exceed the long-term design stress that is depending on the type of glass (annealed, heat strengthened, toughened, chemical treated etc.). From equation B.3 it can be concluded that the maximum stress is directly-proportional to the thickness of the glass and inversely-proportional to the bending radius. This shows that very thin glass panels are needed in order to achieve large curvatures while maintaining the stress under the limit strength of the material. However, the bending of thin glass panels has the risk of buckling (loss of elastic stability).

### Twisted Float Glass

A twisted panel is a double curved quadrangular panel which has three corner points that lie in the same geometrical plane and one that is located out-of-plane. The linear Kirch-Love theory of plates predicts that, when twisted, the deformed shape is a hyperbolic paraboloid. This means that the edges remain straight and the constraint reactions are out-of-plane forces concentrated in the corners which facilitate the twisting of glass panels for façade application (Galuppi et al., 2014). One of the first applications of cold formed twisted float glass is in the City Hall in Alphen aan de Rijn, the Netherlands, by the company Octatube (van Herwijnen et al., 2004). After installation of the twisted panels, there seemed to be a distortion of the panes which gave rise to questions about the exact deformations of twisted glass panels. These questions led to further research of the deformation behaviour of twisted glass panels by Staaks and later on Van Laar continued this research.

The research to the deformation behaviour of twisted glass panels resulted in the conclusion that two modes are visible when twisting the panels. The first mode has a double curved deformation pattern. One diagonal is concave, the other diagonal is convex and the plate edges remain straight. One of the diagonals becomes straight in the second mode, the other diagonal is becoming more curved and the edges are also becoming curved. This behaviour is firstly observed in physical experiments, after which numerical analysis of a plate model are performed. The numerical analysis resulted in a formula that predicts the moment of instability depending on the geometry. For a square plate (length is equal to width) equation B.4 is governing.

$$\alpha = \frac{dz}{t}, \tag{B.4}$$

In which $dz$ is the deformation of the corner point in $mm$ and $t$ is the plate thickness in $mm$.

Numerical analyses were performed by several researchers, such as Staaks, Van Laar, Hoogenboom and Galuppi, to arrive at a value for alpha for a square plate. However, all of these researches resulted in different values for alpha (Bensend, 2016).

**Table B.2:** Value for the buckling factor ($\alpha$) according to several researches

| **Research** | $\alpha$ |
|---|---|
| Staaks 2003 | 16.8 |
| Van Laar 2004 | 14.3 |
| Hoogenboom 2004 | 11.4 |
| Galuppi 2014 | 16 |

Hoogenboom (2004) proposed in his review of van Herwijnen et al. (2004) a relationship (equation B.5) between corner displacement and buckling for a sheet in which the aspect ratio alpha has to be determined by finite element analysis when a»b.

$$dZ_{instability} = b sin \frac{\alpha a t}{b^2}, \tag{B.5}$$

Galuppi et al. (2014) investigated whether the global stability can be enhanced by stiffening the plate edges with bending-rigid braces. From the FEM analyses is concluded that *"a buckling state may be achieved also for this arrangement, but the global stability limit is higher than in the case of the bare glass plate"* (Galuppi et al., 2014). A remarkable result is that the reaction forces that need to be transmitted by the frame are not point loads as expected from the elastic linear solution presented in the research. This means that the adhesive layer between the glass and the frame is subject to distributed reaction forces along its entire length which diffuses the stress in the adhesive layer. Applying this technique can result in unitized steel-framed elements that can be applied in standardized construction, with a higher stability limit compared to a bare glass plate.

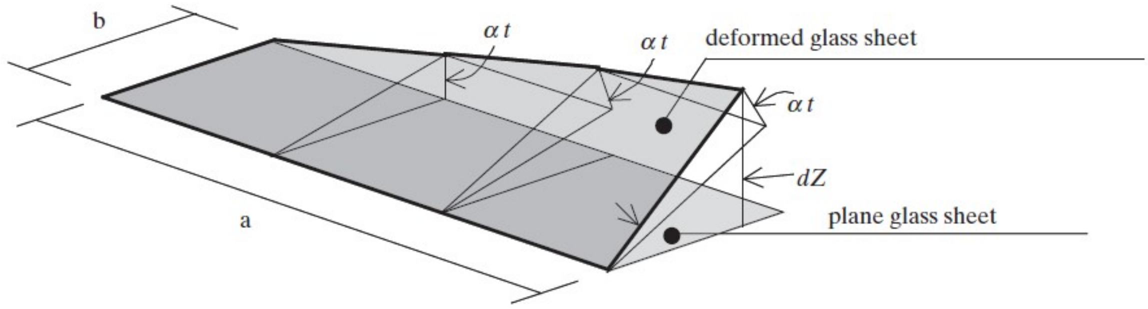



**Figure B.6:** Definition parameters belonging to equation B.5 (Hoogenboom, 2004)

### Cylindrical Thin Glass

Simoen (2016) studied thin glass in cylindrical bended shapes, with boundary conditions including bulkheads that provide extra stiffness to the panel. The research provided insight in the behaviour of thin glass exposed to external loading. The conclusion of the study is that the deformation pattern of thin glass *"almost looks like a pillow"* and that *"the panel tends to become convex near unsupported edges"*. This behaviour can have a negative influence on the stiffness and the appearance of the thin glass panel. Furthermore, there is stated that, to ensure results in FE models, the equivalent thickness of thin glass panels should be extremely precise and that the exact resulting geometry after bending should be precisely studied.

## B.2.2. Exploration Potentials Topic

It is necessary to explore the potential of the application of thin glass in twisted panels to arrive at a conclusion for the feasibility of this application. The potentials will be explored by firstly defining the possible problems for the application of thin glass in twisted panels. Hereafter, a simplified mechanical model will be composed and a couple of simple analysis will be performed on this model in order to investigate influence of the thickness for the bending radii and the buckling. Finally, a conclusion will be drawn on the results of the exploration.

### Possible Problem

The previous treated literature shows that the application of thin glass in twisted configuration has a possible contradiction. On the one hand, thin glass has a higher strength and lower thickness and therefore allows higher bending radii. On the other hand, the research of twisting of float glass shows that a lower thickness will result in an earlier switch from mode 1 to mode 2 and loss of stability. The research of Simoen (2016) also demonstrates that a higher curvature resulted in errors in the FE model.

The contradiction between the advantage of the thickness for the bending radius and the in-plate buckling is topic for the short research that is carried out in order to explore the potentials of the use of thin glass in a cold twisted panel.

### Short Research

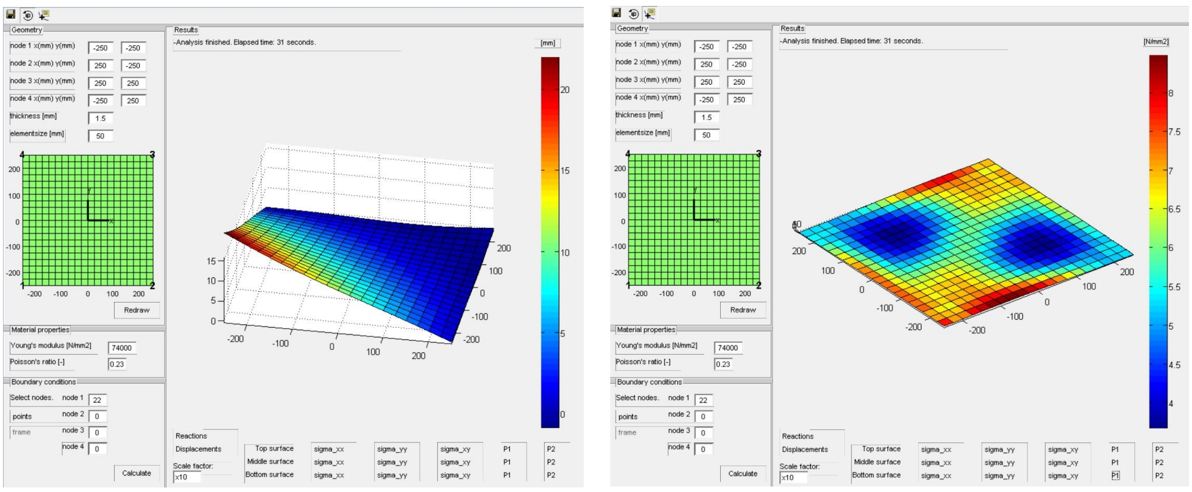
The $dZ_{omslag}$ for a cold twisted panel is calculated with equation B.4 for the different values of $\alpha$ presented in Table B.2, see Table B.3 for the results.

The Plate Bending Application (PBA) is developed for the research to large deformations of panels (Hoogenboom, 2004). The PBA is a special purpose finite element program for computing the stresses in cold bend glass panels. The PBA is used in order to investigate the deformation behaviour of thin glass plates under large (twisting) deformations. The used thickness of the plate is 1.5 mm, because a smaller thickness resulted in no convergence. The E-modulus is 74,000 $N/mm^2$ and the poisson's ratio is 0.23. Change from mode 1

**Table B.3:** $dZ_{omslag}$ calculated for different $\alpha$ presented in B.2

| $t[mm]$ | $\alpha_{Staaks}$ | $\alpha_{VanLaar}$ | $\alpha_{Hoogenboom}$ | $\alpha_{Galuppi}$ |
|---|---|---|---|---|
| 1.5 | 25.2 | 21.5 | 17.1 | 24.0 |
| 1.4 | 23.5 | 20.0 | 16.0 | 22.4 |
| 1.3 | 21.8 | 18.6 | 14.8 | 20.8 |
| 1.2 | 20.2 | 17.2 | 13.7 | 19.2 |
| 1.1 | 18.5 | 15.7 | 12.5 | 17.6 |
| 1.0 | 16.8 | 14.3 | 11.4 | 16.0 |
| 0.9 | 15.1 | 12.9 | 10.3 | 14.4 |
| 0.8 | 13.4 | 11.4 | 9.1 | 12.8 |
| 0.7 | 11.8 | 10.0 | 8.0 | 11.2 |
| 0.6 | 10.1 | 8.6 | 6.8 | 9.6 |
| 0.5 | 8.4 | 7.2 | 5.7 | 8.0 |
| 0.4 | 6.7 | 5.7 | 4.6 | 6.4 |
| 0.3 | 5.0 | 4.3 | 3.4 | 4.8 |
| 0.2 | 3.4 | 2.9 | 2.3 | 3.2 |

to mode 2 is expected between dZ of 17 and 22 mm (see Table B.3). A displacement of 22 mm is applied at a square glass plate of 500 mm by 500 mm. The results are presented in Figure B.7.



**(a)** Displacements $[mm]$ **(b)** Principal stresses $[N/mm^2]$

**Figure B.7:** Results of PBA analysis for dZ=22 mm

The results show that the stresses due to the cold twisting are relatively small compared to the strength of the glass. This is at a small displacement of one corner (22 mm) compared to the dimensions of the plate. However, when the displacement is increased the PBA analysis does not convergence because buckling of the plate occurs.

## B.3. Topic 3: Tensioned Panels

This section treats first a short overview of theory relevant for tensioned thin glass panels: testing of the tensile strength and analysis of cables. Then the feasibility of the topic is treated in which the possible problems and the short research are presented.

### B.3.1. Theory Tensioned Façade

The results of relevant researches are presented in the following section and will form the theoretical background on which the feasibility of the topic will be explored.

#### Bending Tensile Strength of Glass

One of the concerns of using thin glass in structural applications is the uncertainty of the actual strength of the glass. Existing strength testing methods, such as the four-point bending test or ring on ring test, described in the standards (e.g. EN 1288) are not suitable for the geometrical non-linearity of the thin glass. Several papers published different test set-ups that might be used for alternative determination of the ultimate bending strength of thin glass. Neugebauer (2016) investigated these different configurations and analysed the applicability of the methods for the determination of the ultimate bending strength of thin glass.

Neugebauer concluded that the size-effect plays a part in the determination of the bending strength of thin glass. Therefore it is stated that it is necessary to *'find an accurate balance between size of the effective area, in which the measured stress can be assumed as homogeneous, and sensitivity related to imperfections and non-linear effects'* (Neugebauer, 2016). The most promising test scenario, according to Neugebauers research, is the bending with constant radius with influence of edge strength. However, further research related to the applicability of this scenario is required.

#### Analysis of Cables

Depending on the load configuration, the shape of the cable will be parabolic or a hyperbolic cosine curve. The cable deforms according to the parabolic curve when a load is uniformly distributed along the horizontal projection (Figure B.8 b). While the cable shape can be described by a hyperbolic cosine curve when it sags under the action of its own weight (Figure B.8 c). The first configuration matches best with the loading conditions of the façade by a perpendicular wind load. Therefore, the choice is made to approximate the behaviour of the tensioned façade under a wind load by the behaviour of a parabolic cable under a uniformly distributed load.

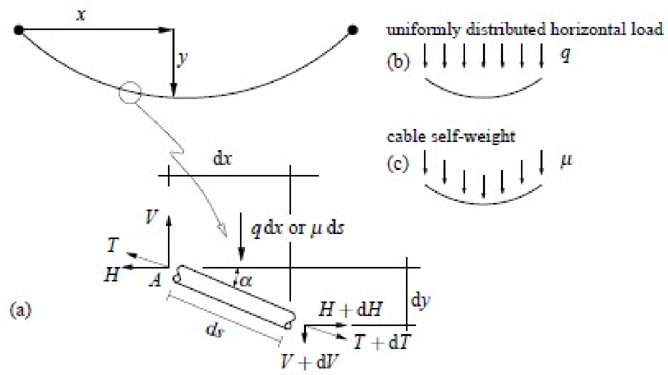



**Figure B.8:** Forces in parabolic cable and catenary (Simone, 2011)

Considering Figure B.8 the following equations can be derived, as presented in Simone (2011). In a parabolic cable, the equilibrium in the vertical direction is:

$$\frac{dV}{dx} = -q \tag{B.6}$$

In which $dV$ is the change in vertical force in $N$, $x$ is the change in horizontal distance in $mm$ and $q$ is the distributed load in $N/mm$.

The rotational equilibrium around point A, neglecting second order terms of the type $(dx)^2$ gives:

$$V = H\frac{dy}{dx} \tag{B.7}$$

In which $H$ is the horizontal force in $N$ and $dy$ is the change in vertical distance in $mm$.

The relation between the deflection y and the applied load q can be expressed by:

$$-H\frac{d^2y}{dx^2} = q \tag{B.8}$$

Successive integration of equation B.8 gives:

$$y = -\frac{qx^2}{2H} + xC_1 + C_2 \tag{B.9}$$

In which $C1$ and $C2$ are integration constants.

The integration constants can be determined by considering $y(0) = 0$ and $y(l) = 0$, where l is the cable span in mm. Inserting the boundary conditions gives:

$$y = \frac{q}{2H}x(l-x) \tag{B.10}$$

and

$$V = q(\frac{l}{2} - x) \tag{B.11}$$

## B.3.2. Exploration Potentials Topic

It is necessary to explore the potential of the application of thin glass in stiffened flat panels to arrive at a conclusion for the feasibility of this application. The potentials will be explored by firstly defining the possible problems for the application of thin glass in stiffened flat panels. Hereafter, a conclusion will be drawn on the results of the exploration.

### Possible Problem

The basic principle of a tensioned façade is that all the external loads (such as wind loads) are transferred by tensile forces in the panels. In order to realise the capacity to transfer these external forces to the supporting structure it is necessary to pretension the façade.

The material glass can be compared to concrete: it is very strong in compression, but weak in tension due to imperfection sensitivity. The possible problem is that the tensile stresses in the façade panels, due to the pretension and external loads, exceed the ultimate tensile strength of the material. Failure of the whole façade element will occur when the ultimate tensile strength is exceeded. Therefore it is important to make a first estimation of the pretension needed to minimize the deflections due to the external loads and to investigate the occurring tensile stresses in the façade panels due to these forces.

### Short Research

The behaviour of a tensioned façade element can be approached by the behaviour of a parabolic cable, as stated previously (see Figure B.9). Equation B.6 to B.11, as explained in the literature section, are used for the numerical analysis of the cable.

The first step of the short research is the determination of the deflection due to a perpendicular wind load with the use of equation B.6. From the results in Figure B.10 it can be seen that a minimal pretension of 200,000 N for decreasing the deflection to a maximum of 200 mm when a wind load is present.

The second step is to determine the stresses due to the wind load. This is determined by firstly calculating the vertical force in the cable due to the wind load by using equation B.11. Hereafter the tension force over the length of the cable can be calculated by using the geometry. Lastly, the tensile stresses due to the tension force can be calculated.

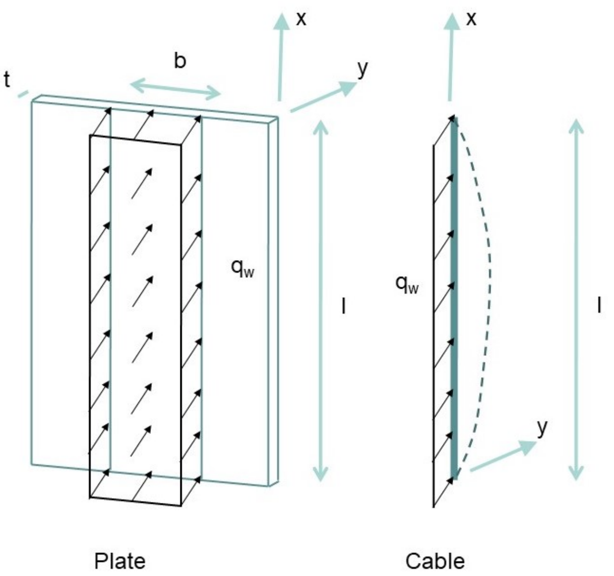



**Figure B.9:** Simplification of façade structure to cable

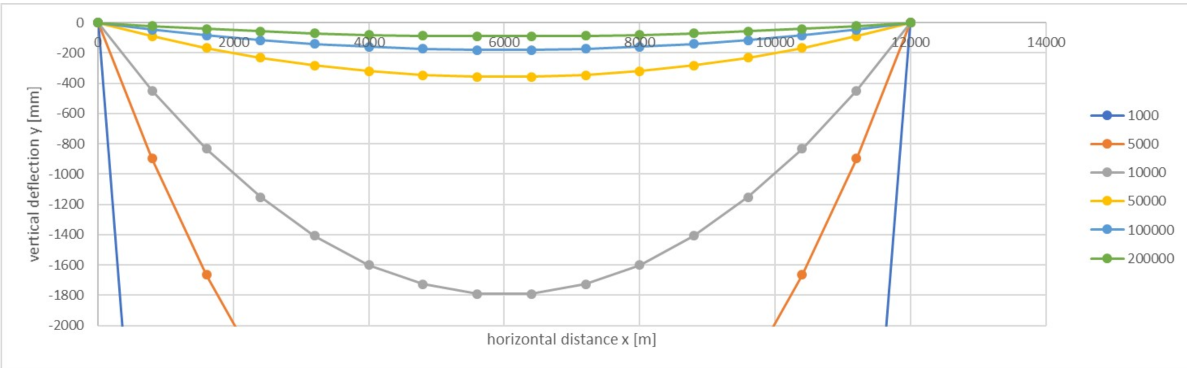



**Figure B.10:** Deflection of a parabolic cable with horizontal pretension variation from 1,000 N to 200,000 N

The tensile strength of the glass panel is assumed to be 160 MPa (Simoen, 2016). From the results in Figure B.11 it can be seen that the stresses due to a pretension of 200 N exceed the tensile strength of the glass. Therefore, it can be concluded that a maximum pretension of 100 kN can be applied in combination with the given load. When a higher pretension is applied, the tensile strength of the glass will be reached and the glass will fail.

| H [N] \ x [mm] | 0 | 800 | 1600 | 2400 | 3200 | 4000 | 4800 | 5600 | 6400 | 7200 | 8000 | 8800 | 9600 | 10400 | 11200 | 12000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 | 6.08276 | 5.29528 | 4.51221 | 3.73631 | 2.97321 | 2.23607 | 1.56205 | 1.07703 | 1.07703 | 1.56205 | 2.23607 | 2.97321 | 3.73631 | 4.51221 | 5.29528 | 6.08276 |
| 5000 | 7.81025 | 7.21388 | 6.66033 | 6.16117 | 5.73062 | 5.38516 | 5.14198 | 5.01597 | 5.01597 | 5.14198 | 5.38516 | 5.73062 | 6.16117 | 6.66033 | 7.21388 | 7.81025 |
| 10000 | 11.66190 | 11.27120 | 10.92520 | 10.62826 | 10.38460 | 10.19804 | 10.07174 | 10.00800 | 10.00800 | 10.07174 | 10.19804 | 10.38460 | 10.62826 | 10.92520 | 11.27120 | 11.66190 |
| 50000 | 50.35871 | 50.26967 | 50.19323 | 50.12943 | 50.07834 | 50.03998 | 50.01440 | 50.00160 | 50.00160 | 50.01440 | 50.03998 | 50.07834 | 50.12943 | 50.19323 | 50.26967 | 50.35871 |
| 100000 | 100.17984 | 100.13511 | 100.09675 | 100.06478 | 100.03919 | 100.02000 | 100.00720 | 100.00080 | 100.00080 | 100.00720 | 100.02000 | 100.03919 | 100.06478 | 100.09675 | 100.13511 | 100.17984 |
| 200000 | 200.08998 | 200.06759 | 200.04839 | 200.03240 | 200.01960 | 200.01000 | 200.00360 | 200.00040 | 200.00040 | 200.00360 | 200.01000 | 200.01960 | 200.03240 | 200.04839 | 200.06759 | 200.08998 |

stress in N/mm2

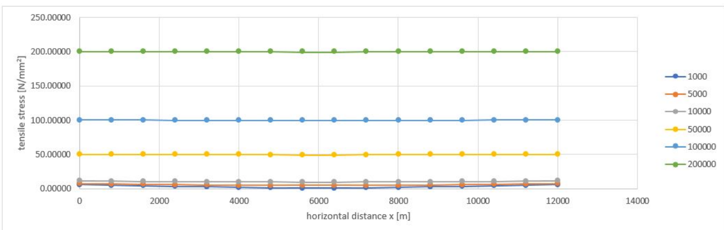



**Figure B.11:** Excel results for the stress in the cable due to the horizontal pretension variation from 1,000 N to 200,000 N

# B.4. Topic 4: Stiffened Flat Panels

This section treats first a short overview of theory relevant for stiffened flat panels in greenhouse application: greenhouse covering and laminated glass panels. Then the feasibility of the topic is treated in which the possible problems and the short research are presented.

## B.4.1. Theory Stiffened Glass for Greenhouses

The results of relevant researches are presented in the following section and will form the theoretical background on which the feasibility of the topic will be explored.

### Greenhouse Covering

A greenhouse consists out of a lot of systems that have to be well integrated to function in the best way possible. The structural system is made up of the framing, the flooring and the covering. This part treats the most important aspects of the greenhouse covering.

The covering of greenhouses has an enormous influence on the crop production capability of the greenhouse system. The covering of the greenhouse drastically affects the amount of type of solar radiation of the plant canopy which result in direct and indirect effects. The plant growth is directly affected by the used covering material. The micro-climatic factors inside the greenhouse, such as air humidity and carbon dioxide concentration, are indirectly influenced by the used covering.

*Materials*
There are three general types of coverings used for greenhouses:

- Glass
- Plastic films
- Rigid plastic panels

Plastics have revolutionized the greenhouse industry and many new greenhouses are covered with plastics. This caused the use of fibre glass to drop (Giacomelli and Roberts, 1993). Plastics are lightweight and are an economical choice. However, plastics have a limited lifetime due to degradation of the physical properties by exposure to UV, pesticides and weathering. Glass is a traditional covering material for greenhouses because it is an attractive, very transparent and formal (in appearance) covering material. However, it is not the most economic choice, because it is relatively heavy (thickness varies from 2 to 6 mm (Ponce et al., 2014)) which results in a more rigid supporting structure. Glass is quite inert, compared to plastics. and can be used for many decades because it is resistant to radiation, air pollutant degradation and it maintains the initial radiation transmission. A dominant drawback of glass is its vulnerability to catastrophic losses caused by hail.

### Lamination Thin Glass

There are two different kind of configurations that can be distinguished when laminating thin chemically treated glass:

- To one or more layers of annealed/heat treated glass
- To a different material such as polycarbonate

Overend et al. (2014) researched the first configuration, the lamination of the chemically strengthened thin glass to one or more layers of annealed/heat treated glass, by proposing a new generation of laminated hybrid-glass units, built-up from plies of chemically strengthened glass, conventional polymer interlayers and heat treated/annealed glass, that aim to outperform conventional laminated glass units. The paper concluded that *"laminated hybrid-glass units can achieve significant post-fracture stiffness and their post-fracture strength can equal or exceed the strength at first fracture"*.

Leonhard et al. (2015) researched also the first configuration, by proposing a light-weight hybrid glass pane for the use in automotive design. The research investigated the configuration of a chemically strengthened thin (0.7 mm) Corning Gorilla Glass ply laminated to a ply of fully strengthened soda-lime glass (2.1 mm). A variety of impact tests showed that the hybrid glass pane has a higher robustness in the ball drop, ball bearing, and hail impact testing.

Weimar (2012) researched the second configuration, the lamination of thin glass to a different material such as polycarbonate, to investigate if glass-polycarbonate composite panels can be used as a replacement of the common laminated safety glass. The paper concludes that it is possible to make a material-efficient design of glass-polycarbonate composite panels with the current state of the art.

### B.4.2. Exploration Potentials Topic

It is necessary to explore the potential of the application of thin glass in stiffened flat panels in order to arrive at a conclusion for the feasibility of this application. The potentials will be explored by firstly defining the possible problems for the application of thin glass in stiffened flat panels. Finally, a conclusion will be drawn on the results of the exploration.

#### Possible Problem

The previous literature concludes that the application of thin glass in stiffened panels for greenhouse covering can be beneficial for weight reduction and increased impact strength. However, some possible problems need to be explored in order to look into the feasibility of this application.

In general, the stress in the glass increases when the thickness of the glass decreases. This means that higher stresses will be present in thin glass when the same loading conditions are applied. However, these stresses will most likely not give problems because the strength of the thin glass is higher due to the chemically treatment. The reduced thickness will also lower the stiffness of the panel due to the decrease moment of inertia. The stiffness of the thin glass panel should be increased before the panel can be used in greenhouse application. The different possibilities already presented in the literature can form a base from which the potentials can be researched.

The solar radiation is an important design factor for the greenhouse design. However, the solar radiation properties of the thin glass panels are not yet researched. A research should be performed in order to investigate the influence of the use of thin glass instead of traditional glass on the crop growth.

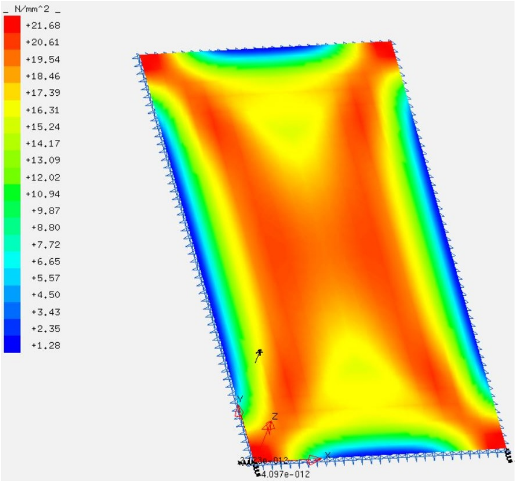
The impact strength of the thin glass should be researched in order to check if the application of thin glass will reduce the hail damage. The impact strength of thin glass is not yet researched and therefore no conclusions can be drawn on the difference between the impact behaviour of traditional glass and thin glass. Therefore it is not possible to simply use the calculation rules for the impact tests of traditional glass to verify the impact strength of thin glass. This means that numerical and experimental research is needed in order to determine the impact strength of thin glass.

#### Short Research

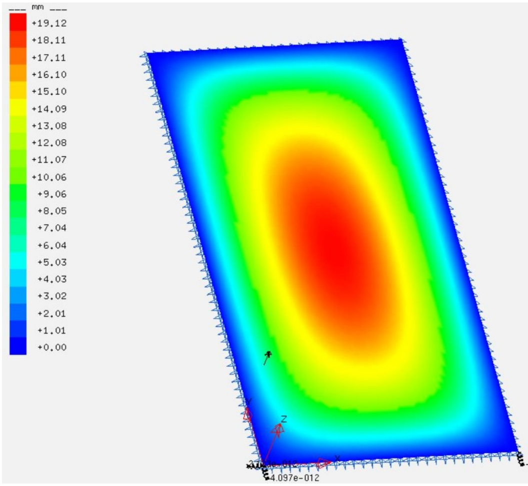
The choice is made to investigate the change in deflections and stresses when a thin glass panel is used instead of the regular float glass. The program SJ Mepla is used for the creation and analysis of the FE model. A panel of 1125 by 2119 mm is created in the program, because this are regular dimensions of glass covering panels. The plate is simply supported along the edges and the dead load and equally distributed load are applied. The distributed load is 0.001 $N/mm^2$ in the z-direction.

The general rule is that a linear analysis can be performed when the deformation is smaller than half of the thickness ($w < t/2$). The assumption is made that the deformations of the glass plate will be larger ($w > t/2$) and this is why there is chosen to perform a geometrical non-linear analysis. The thickness of the plate is varied from 4 mm down in order to see the difference between the commonly applied float glass and thin glass.

The results of the analysis are shown in Figures B.12 and B.13. It can be seen that the deformations and stresses are larger in the thinner panel under the same load conditions. The smallest thickness that was able to be analysed with these dimensions, loads and supporting conditions was a thickness of 2.5 mm. This is quite a large thickness for a thin panel. The deformations were too large when smaller thickness was used with the same boundary conditions and the analysis did not converge. From this it can be concluded that it is necessary to stiffen the flat thin panels when they are applied with the same boundary conditions in the greenhouse covering.

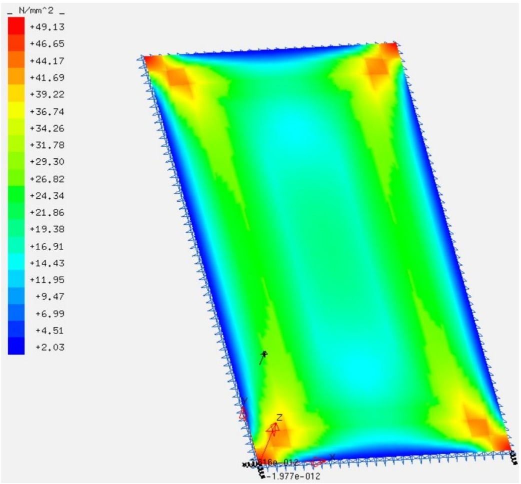



**(a)** Stresses Sp+ $[N/mm^2]$

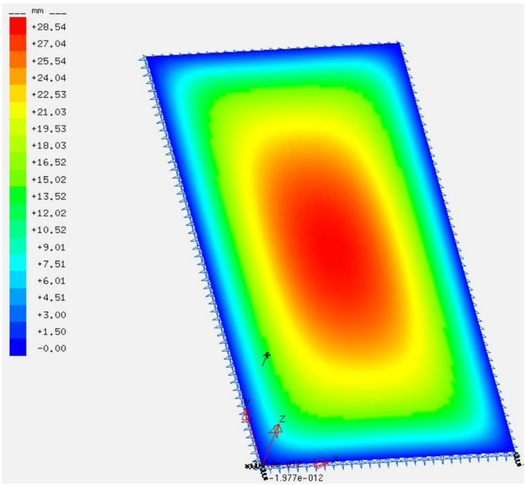



**(b)** Deformations w $[mm]$

**Figure B.12:** Results of Mepla analysis for t=4 mm




**(a)** Stresses Sp+ $[N/mm^2]$

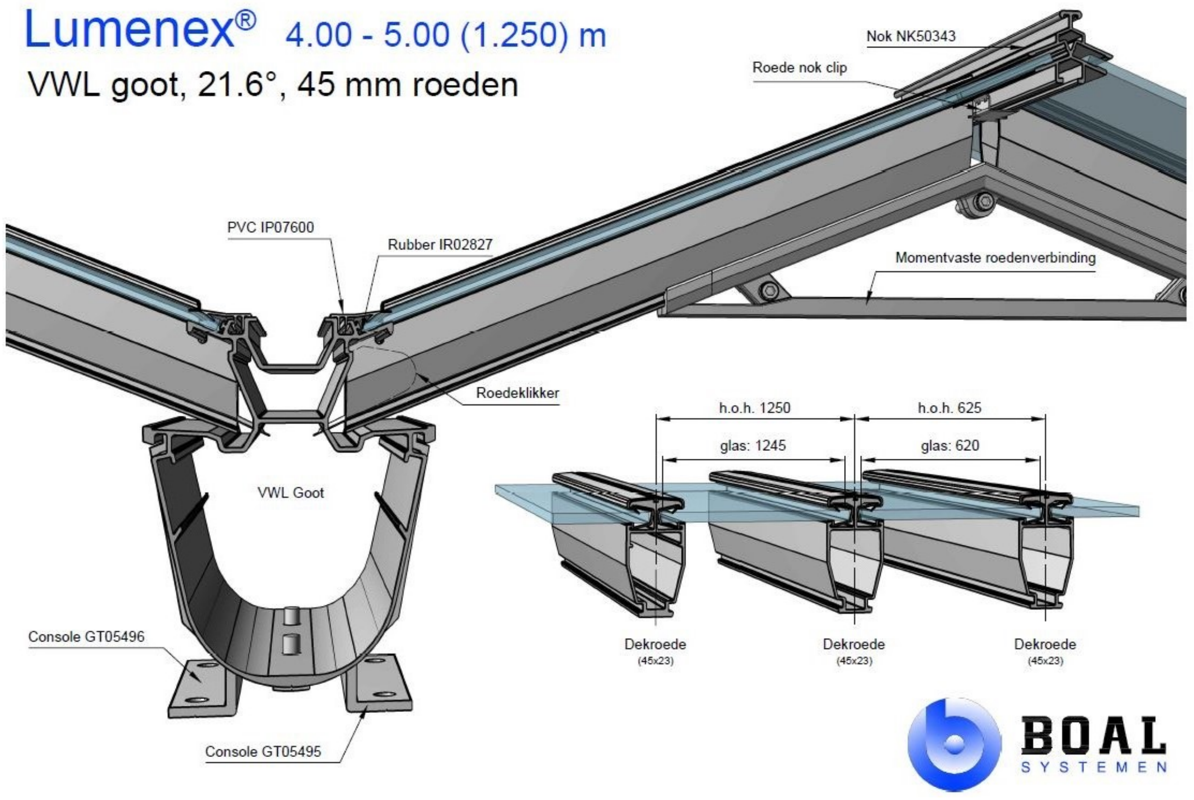



**(b)** Deformations w $[mm]$

**Figure B.13:** Results of Mepla analysis for t=2.5 mm

# C
# Aluminium System

An overview of the general used aluminium supporting system for a Venlo greenhouse for 4 mm regular float glass panels is shown in this Appendix. This system is developed by Boal systems and the systems might differ slightly per greenhouse system company.



# D

# Loads Determination

This Appendix presents the determination of the loads that are shown and used in Chapter 9. Firstly, the different load combinations are shown. Hereafter the determination of the individual loads is shown.

The loads are determined using the Dutch standard for greenhouse design NEN 3859 (Normcommittee 351 037 "Kasconstructies", 2012), the general Dutch standard for load determination NEN 1991-1-1 (Normcommittee 351 001 "Technische Grondlagen voor Bouwconstructies", 2002) and the ISSO 88 Quality requirements for greenhouses (ISSO Foundation, 2015).

## D.1. Load Combinations

The load combination used are assumed to be ULS, as stated in Chapter 9. The load combination factors that are used to determine the load combination values are presented in Table D.1.

**Table D.1:** Load combination factors (Normcommittee 351 037 "Kasconstructies", 2012)

| **Load Combination** | **Permanent** $\gamma_{G,1}$ | **Wind** $\gamma_{Q,1}$ | **Snow** $\gamma_{Q,2}$ | **Rain** $\gamma_{Q,3}$ | **Hail** $\gamma_{Q,4}$ |
|---|---|---|---|---|---|
| Perm. + wind | 1.021 | 1.275 | - | - | - |
| Perm. + snow | 1.021 | - | 1.275 | - | - |
| Perm. + rain | 1.021 | - | - | 1.275 | - |
| Perm. + hail | 1.021 | - | - | - | 1.275 |

## D.2. Permanent Load

The permanent load usually exist of two parts: the dead load (own weight) and the imposed load. The Dutch design standard for general actions on buildings stated that imposed loads do not need to be applied for this research. As they do not relate to a transparent roof finish which shows that no support structure is present under the roof covering (Normcommittee 351 001 "Technische Grondlagen voor Bouwconstructies", 2002, p. 7). Therefore only the dead load is taken into account for the permanent load.

The permanent load can be calculated by Equation D.1.

$$G_{k1} = \rho_{glass} * t \tag{D.1}$$

In which $\rho_{glass}$ is the density of glass in $kN/m^3$ and $t$ is the thickness of the glass panel in $m$.

Using the properties this yields a dead load of:

$$G_{k1} = 25 * 0.00055 = 0.01375 kN/m^2 \tag{D.2}$$

## D.3. Wind Load

The wind load on greenhouses will be determined using the NEN3859 design standard (Normcommittee 351 037 "Kasconstructies", 2012, p.32). Equation D.3 will be used to determine the wind load.

$$Q_{k1} = c_s c_d * c_{index} * q_p(z_e) \tag{D.3}$$

In which $c_s c_d$ is the building factor, $c_{index}$ is the wind/area factor and $q_p(z_e)$ is the external pressure load.

For the Venlo greenhouse system $c_s c_d$ = 1.0 can be used, according to the Dutch design standards.

$c_{index}$ is determined according to Appendix B of NEN3859. The governing factor was -0.7 and is therefore used. The negative value of the wind/area factor means that the governing wind load is a wind suction, as shown in Figure D.1.

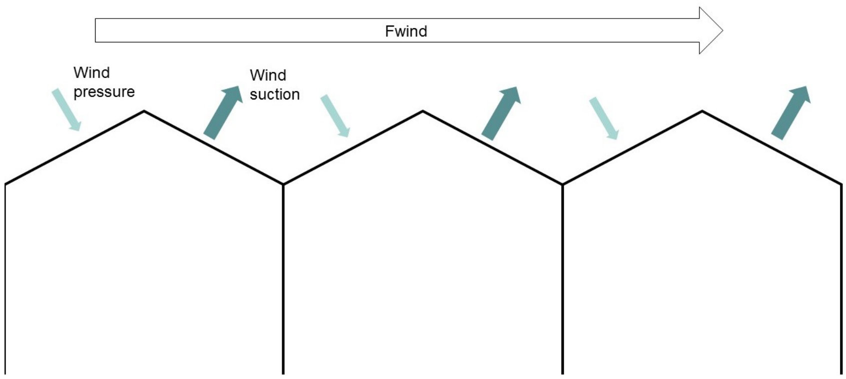



**Figure D.1:** Wind pressure and suction on a Venlo greenhouse system

The external pressure load is determined according to NEN1991-1-1. A height of 7m, wind area I, life span of 15 years and $c_{prob}$ of 0.93 are used and results in an external pressure of $q_p(z_e)$ = 1.3671 $kN/m^2$.

The determined properties are used in Equation D.3 and result in a wind load of:

$$Q_{k1} = 1.0 * -0.7 * 1.3671 = -0.957 kN/m^2 \tag{D.4}$$

## D.4. Snow Load

The snow load on greenhouses will be determined using the NEN3859 design standard (Normcommittee 351 037 "Kasconstructies", 2012, p.33). In reality the snow load will be higher at the lowest point of a slope. However, an evenly distributed snow load is used for this research, because this is easier for the input in the FE model (see Figure D.2).

The snow load can be calculated by Equation D.5.

$$Q_{k2} = \varphi_T * c_t * \mu_i * p_{sn} \tag{D.5}$$

In which $\varphi_T$ is the extreme value reduction factor, $c_t$ is the thermal coefficient, $\mu_i$ is the shape coefficient and $p_{sn}$ is the extreme value of snow at ground level in $kN/m^2$.

For the reference greenhouse it can be stated that according to NEN3859 that:

- $\varphi_T = 0.75$
- $c_t = 0.6$
- $\mu_i = 0.8$
- $p_{sn} = 0.7$ $kN/m^2$

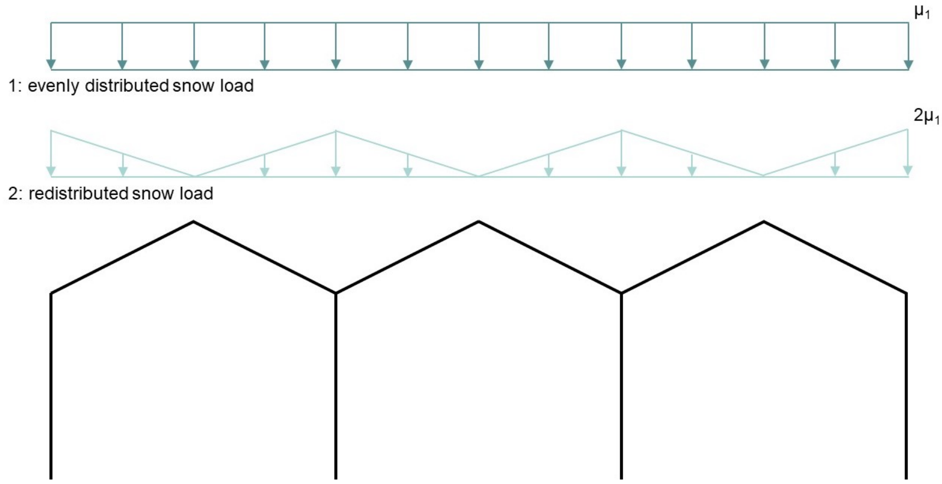



**Figure D.2:** Difference between evenly distributed and redistributed snow load

Filling in the properties in Equation D.5 gives an evenly distributed snow load of:

$$Q_{k2} = 0.75 * 0.6 * 0.8 * 0.7 = 0.252 kN/m^2 \tag{D.6}$$

A minimum value of $Q_{k2}$ = 0.25 $kN/m^2$ should be used for greenhouses of type A15 (hard covering, life span of 15 years). This is smaller than the calculated snow load in Equation D.6 and therefore a value of 0.252 $kN/m^2$ will be used.

## D.5. Rain Load

The rain load on greenhouses will be determined using the ISSO 88 guideline (ISSO Foundation, 2015, p.64,65).

The volume flow of rainwater for a greenhouse rain water system is assumed to be 12 $mm/5min$. The aluminium gutters do not have enough capacity for this amount of water and thus the roof is partly used for the transportation of the water. The permissible water level on a greenhouse covering is generally held at a size of 500 mm, measured along the roof bar. The maximum height of water on the covering can be calculated with Equation D.7.

$$h = sin(\alpha) * s \tag{D.7}$$

In which $\alpha$ is the angle of the covering panels and $s$ is the previously determined 500 mm.

The rain load is not evenly distributed, but an evenly distributed representation of the rain load will be used for the FE model. The evenly distributed rain load can be determined by Equation D.8.

$$Q_{k3} = 0.5 * h * \gamma_w \tag{D.8}$$

In which $\gamma_w$ is the volumetric weight of water in $kN/m^3$.

Substituting the properties in the equation gives a total rain load of:

$$Q_{k3} = 0.5 * sin(26) * 0.5 * 9.8 = 1.0740 kN/m^2 \tag{D.9}$$

## D.6. Hail Load

There are no design standards available for the determination of the hail load on a greenhouse covering. The choice is made to determine the hail impact to get an indication of the hail load.

Hail varies by a number of parameters such as size, density and terminal velocity. These parameters should be researched before an estimation of the hail load can be made.

Hail size varies a lot, even in one hail storm. Sizes from 6 mm and even larger than 120 mm are reported during different storms. The research of TNO (KRI-TNO et al., 1984) showed that the governing size of damaging hail stones is 20 to 30 mm. Therefore this value is used for further calculations.

The density of a hail stone is assumed to be similar to the density of ice, however this is likely to be different in reality. The assumed density for hail is therefore 917 $kg/m^3$.

The resultant velocity of hailstones can be determined by Equation D.10, according to Sharafi et al. (2013).

$$v_r = \sqrt{v_t^2 + v_w^2} \tag{D.10}$$

In which $v_t$ is the terminal velocity in $m/s$ and $v_w$ is the wind velocity in $m/s$.

The wind velocity can be assumed to be 20 m/s, while the terminal velocity can be determined by Equation D.11.

$$v_t = 14.04 * \sqrt{d_n} \tag{D.11}$$

In which $d_n$ is the diameter of the hailstone in $cm$.

The impact energy of a hail stone when hitting the greenhouse covering can be estimated by Equation D.12.

$$KE = 0.5 * m * v_r^2 \tag{D.12}$$

In which $m$ is the load of the hail stone in $kg$.

Filling in the properties of the hail stone in the above mentioned equation for different sizes of the hail stone, gives an overview of the impact energy of hailstones of different sizes. This overview is presented in Figure D.3.

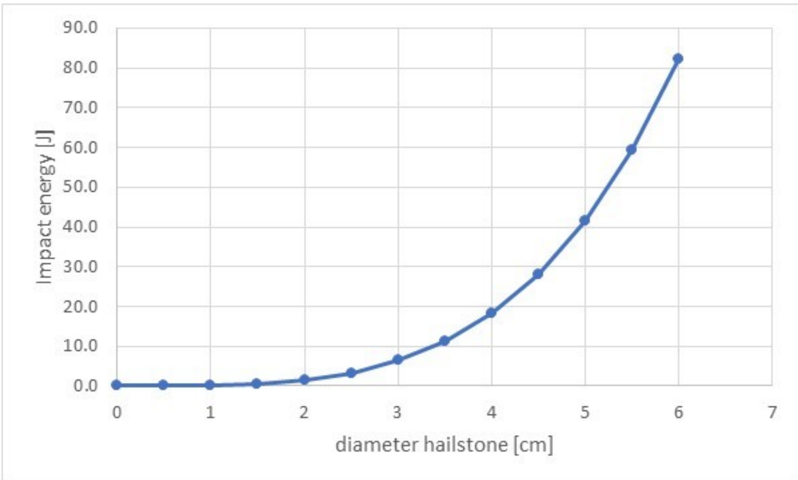



**Figure D.3:** Relation between diameter of hail stone and the impact energy

It is possible to determine the impact energy of a hail stone, as shows in Figure D.3. However, for a representative model of the reality it is necessary to examine the extent of interaction, crushing and deflection of the hail stone and glass panel. The choice is made not to investigate this during the research, because it would be outside of the research scope. Therefore, no hail load will be used during the rest of the numerical and experimental analysis as it would give biased results.

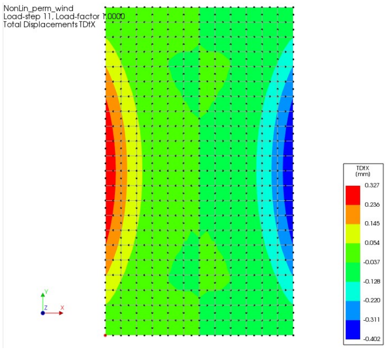
# E

# Results Reference Study

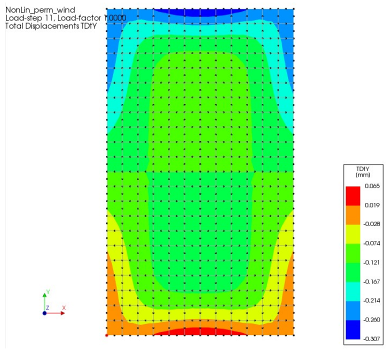
This Appendix presents the contour plots of the deformations and stresses for the different load combinations for the reference study FE models for regular float glass with a thickness of 4 mm. The load steps that are shown are the steps at which the total loads, as determined in Appendix D, are applied.

## E.1. Permanent + Wind

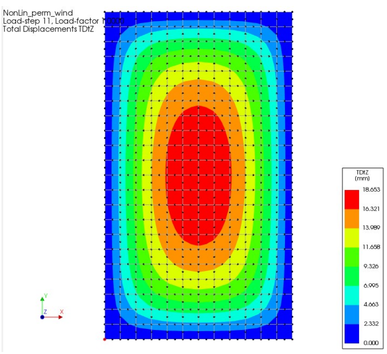
The results of the load combination of the permanent + wind load are presented in Figure E.1.



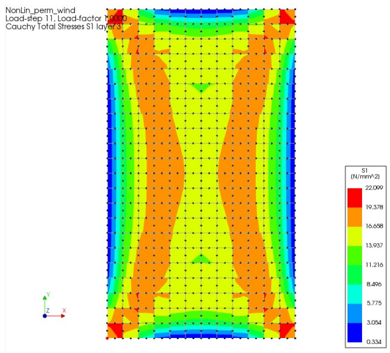

**(a)** Max TX = -0.4 $mm$




**(b)** Max TY = -0.3 $mm$




**(c)** Max TZ = 18.7 $mm$

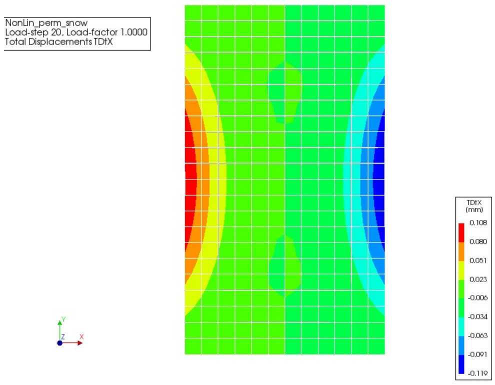



**(d)** Max S1 = 22.1 $N/mm^2$

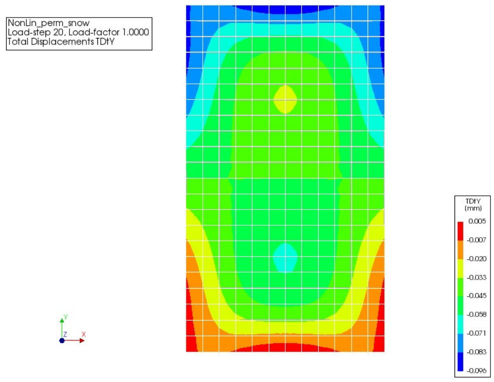
**Figure E.1:** Results non-linear analysis reference model load combination Permanent + Wind

## E.2. Permanent + Snow

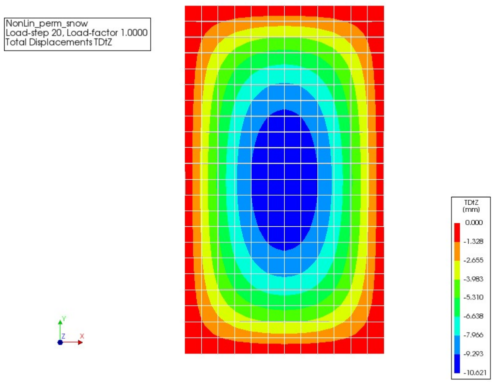
The results of the load combination of the permanent + snow load are presented in Figure E.2.



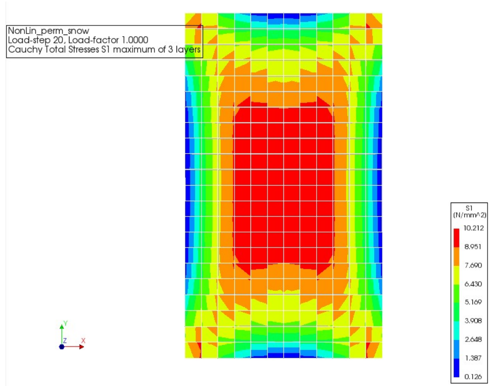

**(a)** Max TX = -0.1 $mm$




**(b)** Max TY = -0.1 $mm$




**(c)** Max TZ = -10.6 $mm$

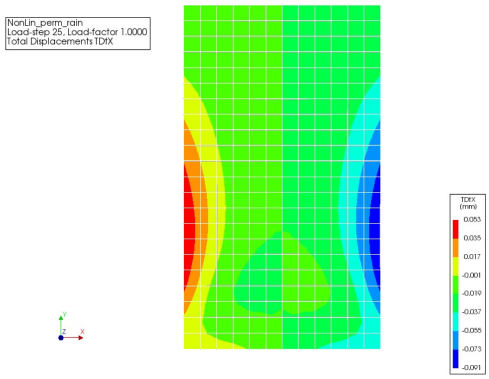



**(d)** Max S1 = 10.2 $N/mm^2$

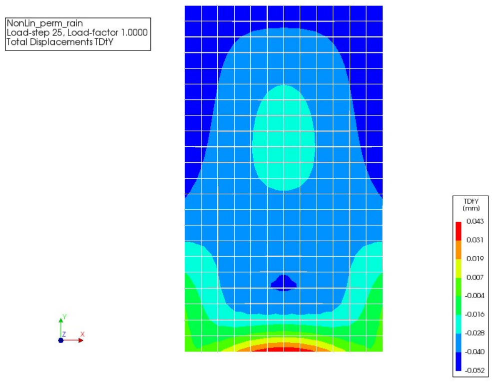
**Figure E.2:** Results non-linear analysis reference model load combination Permanent + Snow

# E.3. Permanent + Rain

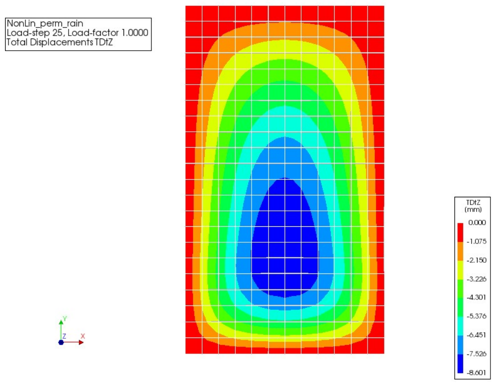
The results of the load combination of the permanent + rain load are presented in Figure E.3.



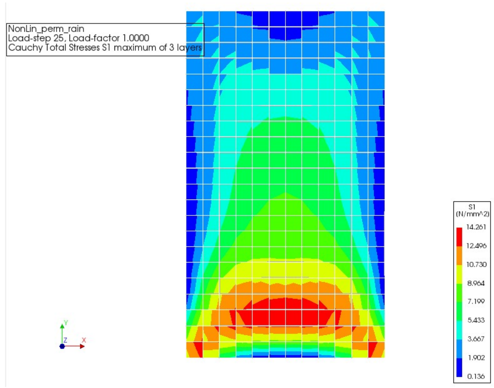

**(a)** Max TX = -0.1 $mm$




**(b)** Max TY = -0.05 $mm$




**(c)** Max TZ = -8.6 $mm$




**(d)** Max S1 = 14.3 $N/mm^2$

**Figure E.3:** Results non-linear analysis reference model load combination Permanent + Rain

# F Experiments

This Appendix presents a description of the test set-up and execution of the experiments mentioned in Chapter 9. Firstly, the general information for the experiments such as problem statement, goal and hypothesis are shown. Secondly, the test set-up is shown. Hereafter, the geometry and preparation of the panels is given. Then the execution procedure of the experiments is presented. Lastly, the processing procedure of the results is treated.

## F.1. General

### F.1.1. Problem Statement

The thin plate theory cannot be used for the thin glass panels to check the analytical behaviour of the plates, because of the small thickness compared to the dimensions of the plate. Therefore, it is necessary to use numerical FE models to determine the behaviour of the greenhouse covering panels and the needed supports.

The FE models developed for the reference system, in Chapter 9, show that the deflection in Z direction is very large and large stresses occur in four points on a short distance from the corners. Based on these models it seems that the stiffness of the thin glass panels is too small for the use in greenhouse covering and thus the stiffness should be increased by either adjusting the supports or using a different stiffening method. A variation study needs to be executed to investigate which stiffening method is most suitable for thin glass panels. However, the results of the numerical analysis must be distrusted at beforehand, because it isn't sure if the FE models represent the behaviour of the panels in a realistic way. This is why the choice is made to execute several experiments on different panel variants, to check the accuracy of the FE models.

### F.1.2. Goal

The goal of the experiment is to investigate the deformation in Z direction when a perpendicular (out-of-plane) load is applied for several stiffening variations and to use the results of the experiment to validate the FE model.

### F.1.3. Hypothesis

The hypothesis is that the deflection in Z direction will be large compared to the geometry, but that the variations of the supports and stiffening methods will result in smaller deflection. It is expected that the results of the experiments and FE model will be comparable, but can differ slightly due to differences in the boundary conditions, load application or material properties.

## F.2. Test Set-up

The test set-up consists of a wooden frame on which the glass panel is placed. The glass panel is supported by the wooden frame on all four sides over a width of approximately 10 mm. The inside dimensions of the wooden frame are 340 by 690 mm, so that the glass panel of 360 by 710 mm fits onto it. Four corner applications are screwed onto the frame to prevent the plate from sliding during the experiment.

A total distributed load ($q_{load}$) is acquired by applying a load with a total weight of 500 grams first in the middle of the plate ($q_{load,mid}$), then at the left side of the plate ($q_{load,left}$) and finally at the right side of the plate ($q_{load,right}$). This sequence is repeated until the required total load is reached ($\approx 9kg$).

The deformations in z direction are measured at two locations by linear potentiometers. The first location is at midspan (coordinates: x = 180, y = 355) and the second at a quarter (coordinates: x = 180, y = 532.5). The linear potentiometers are placed at the downside of the panel, so that the distributed load can be applied at the top of the panel without disturbing the measurement equipment.

Figure F.1 shows the drawings of the set-up design and the realized set-up is shown in Figure F.2.

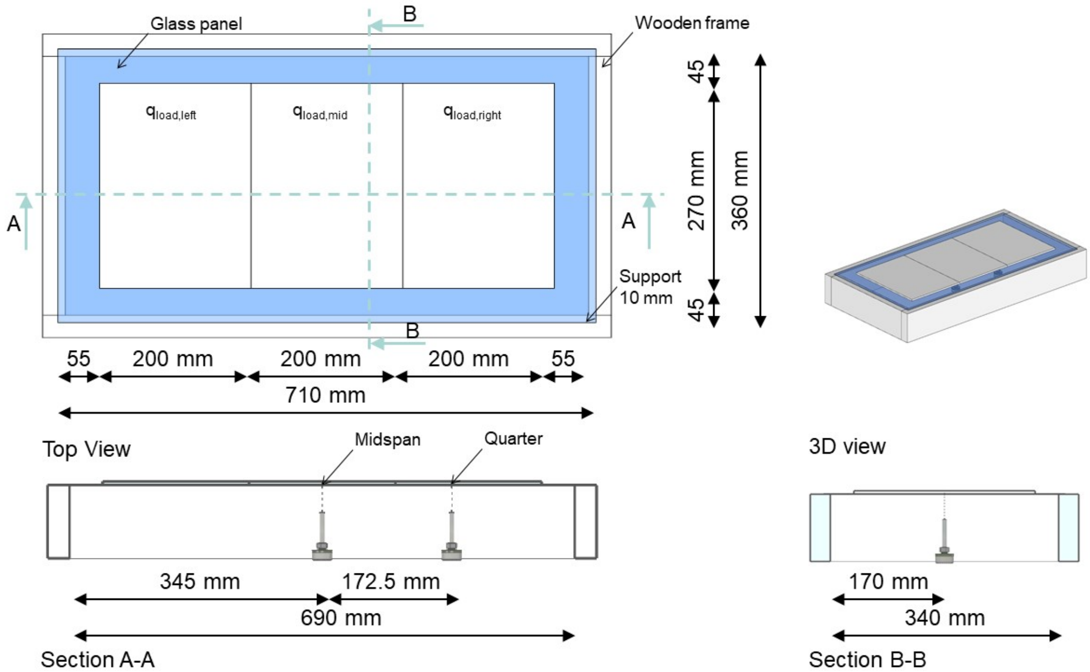
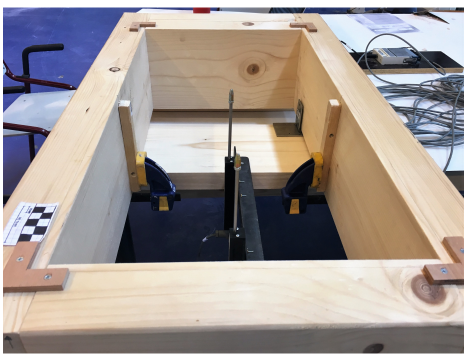



**Figure F.1:** Drawing of test set-up



**(a)** Wooden frame with linear potentiometers

**(b)** Wooden frame with glass and distributed load

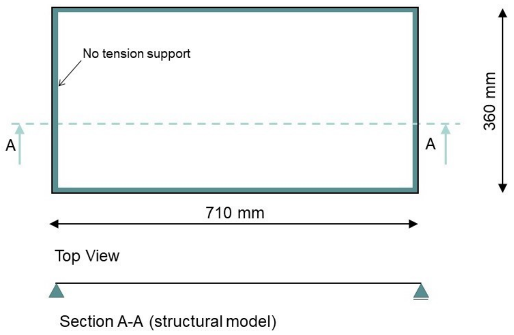
**Figure F.2:** Pictures of prepared test set-up

# F.3. Panels Set-Up

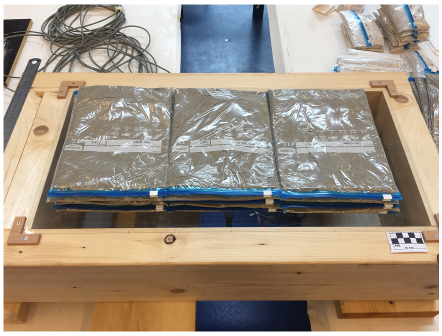
Seven different panel set-ups are tested:

- Simply supported non stiffened single panel
- Four sides clamped single panel
- Simply supported rib stiffened single panel
- Simply supported cable supported single panel
- Simply supported rib sandwich panel
- Simply supported rib and patch sandwich panel
- Simply supported insulating glass unit

The design drawings for the panel set-up and the pictures of the realised panels are shown in Figures F.3 -F.9.

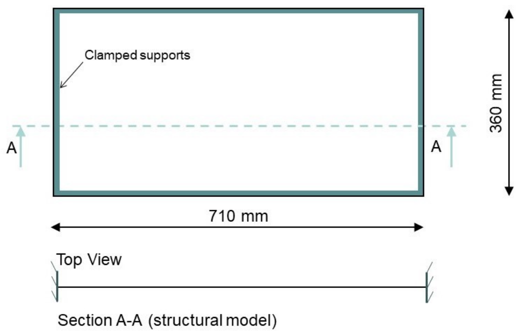



(a) Drawing design set-up

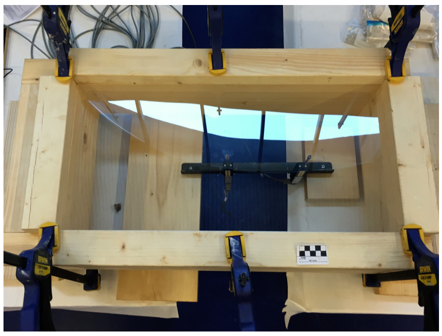


(b) Picture realised panel

Figure F.3: Simply supported non stiffened single panel

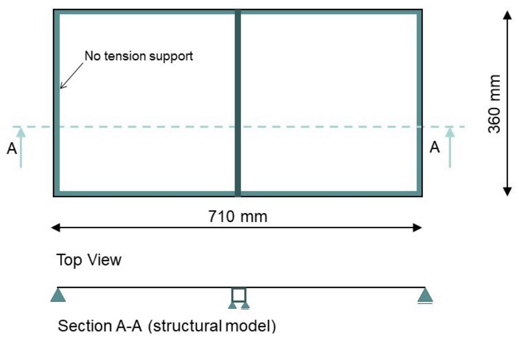



(a) Drawing design set-up



(b) Picture realised panel

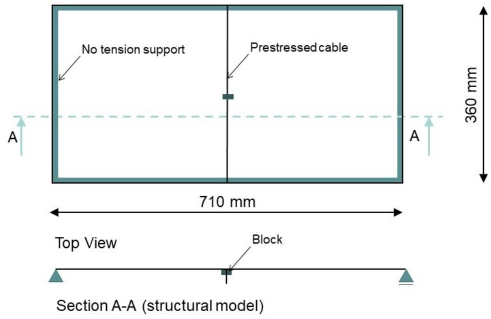
Figure F.4: Four sides clamped single panel



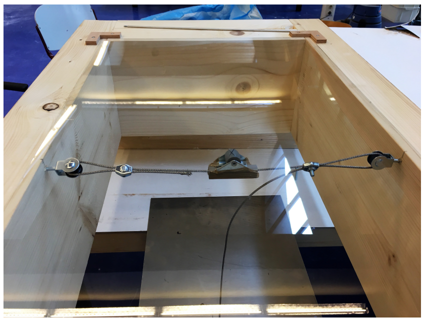

(a) Drawing design set-up

(b) Picture realised panel

Figure F.5: Simply supported rib stiffened single panel

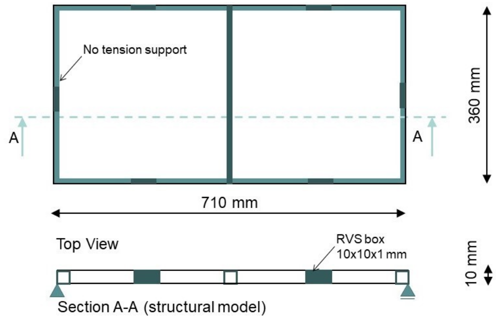



**(a)** Drawing design set-up



**(b)** Picture realised panel

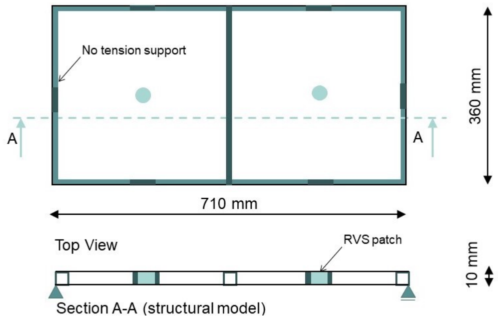
**Figure F.6:** Simply supported cable supported single panel




**(a)** Drawing design set-up

**(b)** Picture realised panel

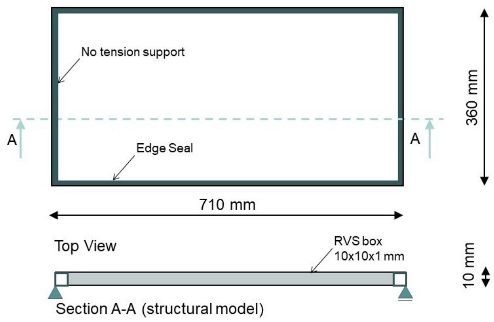
**Figure F.7:** Simply supported rib sandwich panel



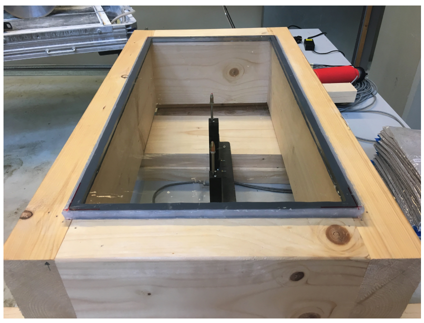

**(a)** Drawing design set-up

**(b)** Picture realised panel

**Figure F.8:** Simply supported rib and patch sandwich panel




**(a)** Drawing design set-up



**(b)** Picture realised panel

**Figure F.9:** Simply supported insulating glass unit

## F.4. Execution

The execution procedure is as following:

- Preparation of panel
- Preparation of supports
- Place panel on wooden frame
- Put linear potentiometers at location midspan and quarter
- Connect linear potentiometers to laptop
- Start measurement on laptop
- Add loads until total load of 9 kg
- Remove loads in same way as application
- Stop and save measurement on laptop

## F.5. Preparation IGU Panel

The hermetically sealed cavity in an insulating glass unit ensures that a certain degree of cooperation between the two blades is present. The external load can therefore be divided between both glass sheets according to NEN2608 when regular float glass is used. For a short term load (such as a wind load) it is assumed that the two panels of the IGU have a 100% cooperation. Therefore half of the load that is used for the other variants is applied on the top and bottom panel in the FE model of the IGU variant.

For the experiment of the insulating glass unit it is necessary that the tested panel is hermetically sealed. The IGU panel for the experiment is fabricated by glueing stainless steel rectangular box sections of 10x10x1 mm to the edges of the plate. Hereafter, the edges are hermetically sealed by adding silicone between the two glass panels on the outside of the box sections. Figure F.10 shows a detail of the silicone sealed edges. The used glue is: Araldite 2013, a grey two component epoxy paste adhesive. The used silicone is: Bison silicone kit glass, an elastic water resistant transparent kit.

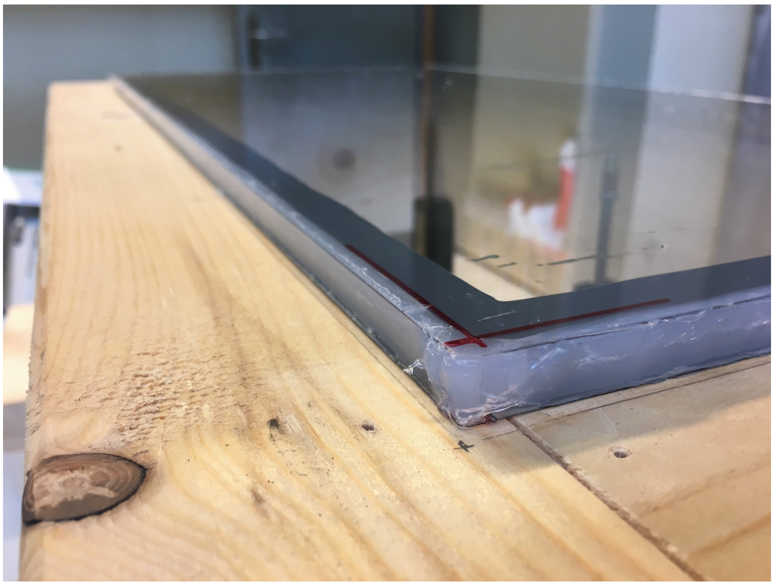


**Figure F.10:** Close-up of sealed edge of IGU panel

An additional experiment is performed on the IGU panel to check if the assumption of the cooperation and load distribution is also valid for the thin glass IGU. A distributed load is applied on the top panel and the deformations are measured at the top and bottom plate at midspan. The bottom deformation is measured by a linear potentiometer, while the top deformation is measured by a dial gauge. The deformations of the top and bottom panel will be compared and when they are similar it can be concluded that cooperation between the panels is present and the IGU panel is hermetically sealed. The results of this experiments are shown in Figure F.11.

The results in Figure F.11 show a small difference in the deformations at midspan for the top and bottom panel. The load is applied on the top panel and therefore it is assumed that the top panel will deflect more than the bottom panel when the panel is not hermetically sealed. However, the results show that the displacements of the bottom panel are larger than the top panel. It is likely that this difference can be explained by the fact that the bottom displacement is measured automatically by a linear potentiometer while the top displacement is measured manually. The conclusion of this additional experiment is that the fabricated IGU panel is hermetically sealed and that the assumption of external load distribution over the two panels as stated in NEN2608 can be used for the set-up of the numerical models.

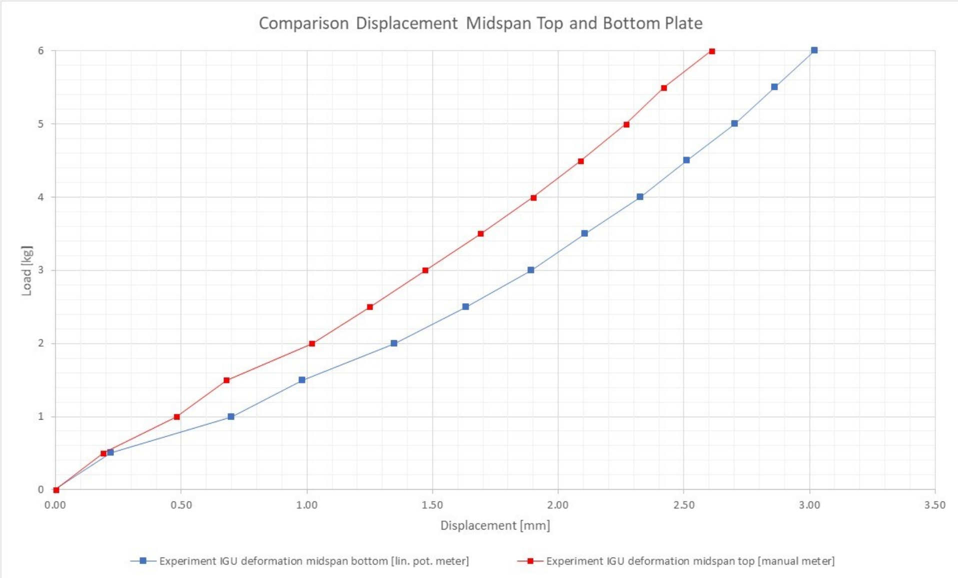



**Figure F.11:** Resulting graph of the displacements at midspan for the executed stiffened panels experiments and the related FE models

## F.6. Processing Results

The displacements in z direction are measured with two linear potentiometers, the type of linear potentiometer that is used is shown in Figure F.12.


**Figure F.12:** Used linear potentiometer

The signals of the linear potentiometer are converted by the NI9219 measurement module and the signal is read by the MP3 program on the laptop. The time and displacement are measured twice per second and the results are saved in an Excel file.

The results in the Excel file are converted to a load-displacement graph. This is necessary, because the results of the FE models are also presented as load-displacement graphs and in this way it is possible to compare the results of the experimental and numerical analyses.

# G

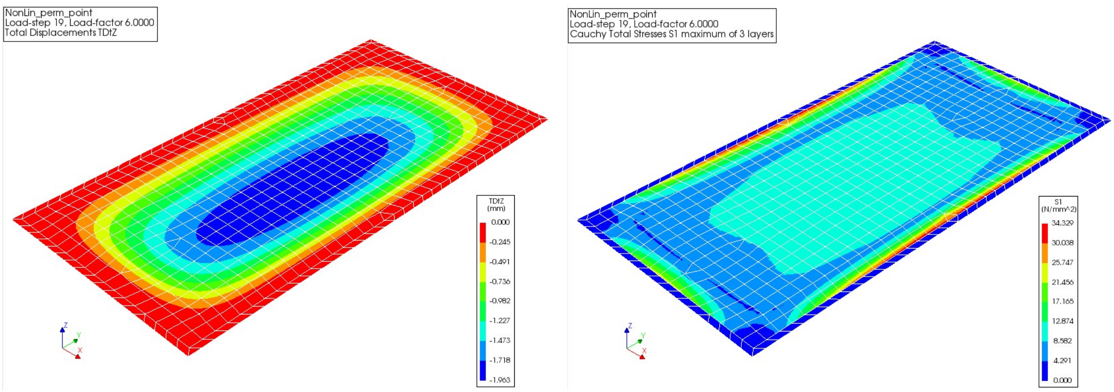
# Results Variation Study

This Appendix firstly presents the contour plots of the deformations and stresses of the thin glass variation study FE models. The load steps that are shown are the steps at which a total load of 9 kg is present at the surface. Hereafter, the load-displacement graphs for the numerical and experimental results for each tested panel are presented.

## G.1. Numerical Results: Contour Plots

### G.1.1. Adjusted Supporting Conditions

#### Four Edges: Fixed Translations and Rotations

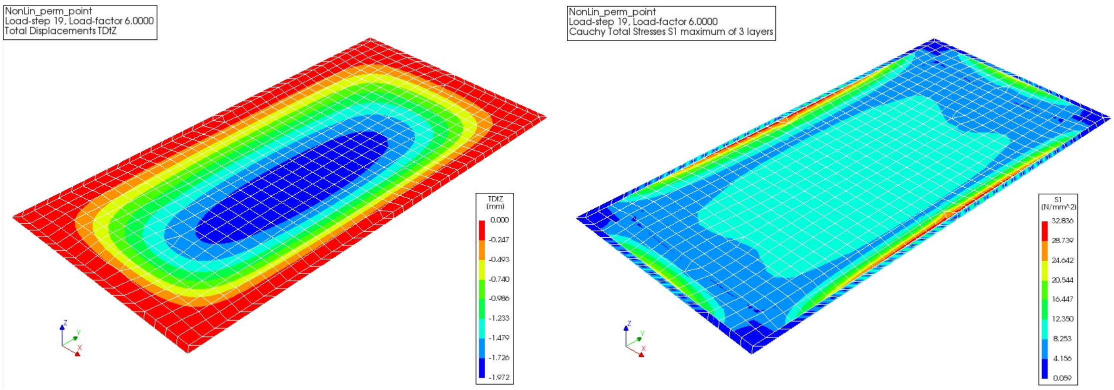



**(a)** Max TZ = -2.0 $mm$

**(b)** Max S1 = 34.3 $N/mm^2$

**Figure G.1:** Contour plot load-step 19 non-linear analysis 4 edges fixed translations and rotations

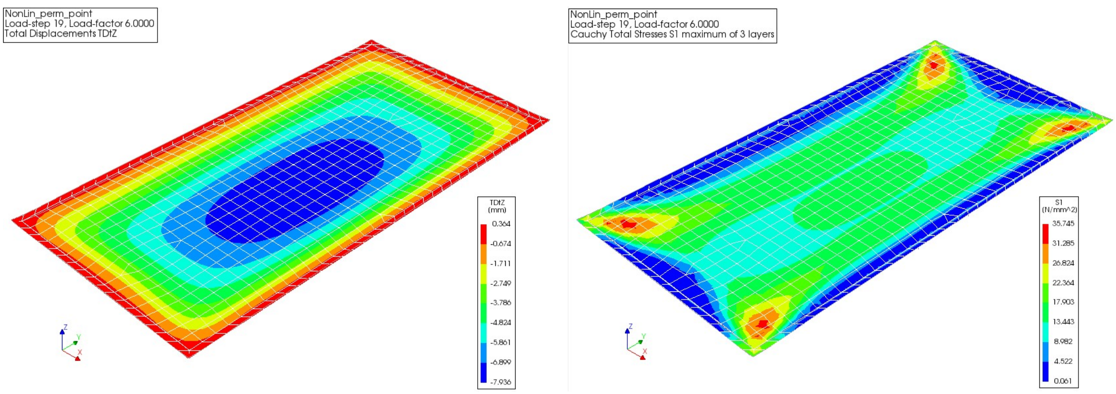
## Four Edges: Fixed Translations, Free Rotations




**(a)** Max TZ = -2.0 $mm$ **(b)** Max S1 = 32.9 $N/mm^2$

**Figure G.2:** Contour plot load-step 19 non-linear analysis 4 edges fixed translations

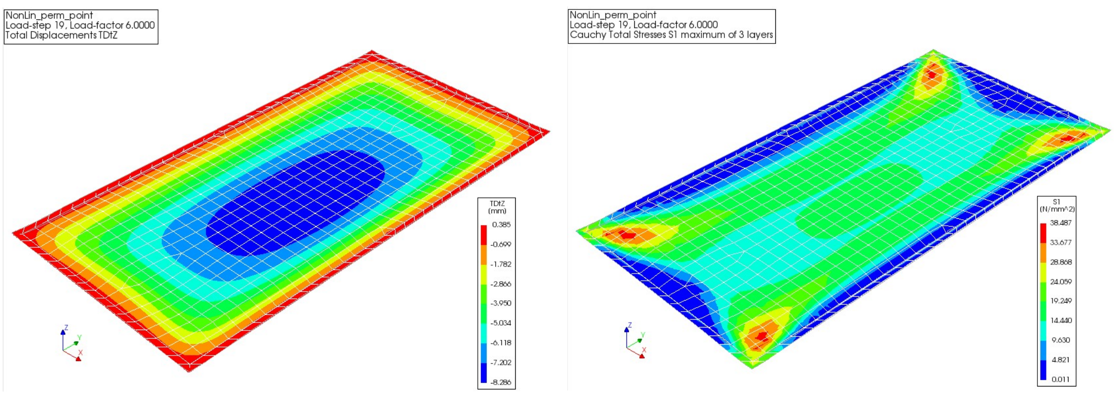
## Two Long Edges: Fixed Translations, Free Rotations




**(a)** Max TZ = -8.0 $mm$ **(b)** Max S1 = 35.7 $N/mm^2$

**Figure G.3:** Contour plot load-step 19 non-linear analysis 2 long edges fixed translations

## Two Short Edges: Fixed Translations, Free Rotations

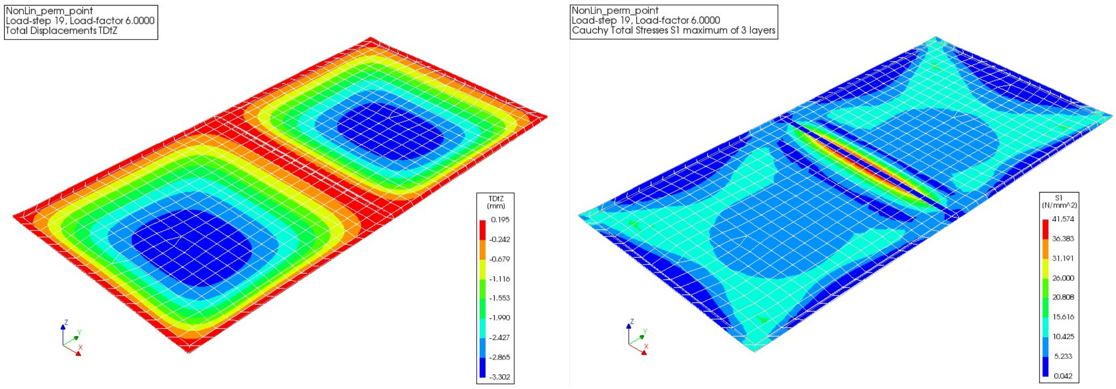



**(a)** Max TZ = -8.3 $mm$ **(b)** Max S1 = 38.5 $N/mm^2$

**Figure G.4:** Contour plot load-step 19 non-linear analysis 2 short edges fixed translations

## G.1.2. Stiffening Plate Itself

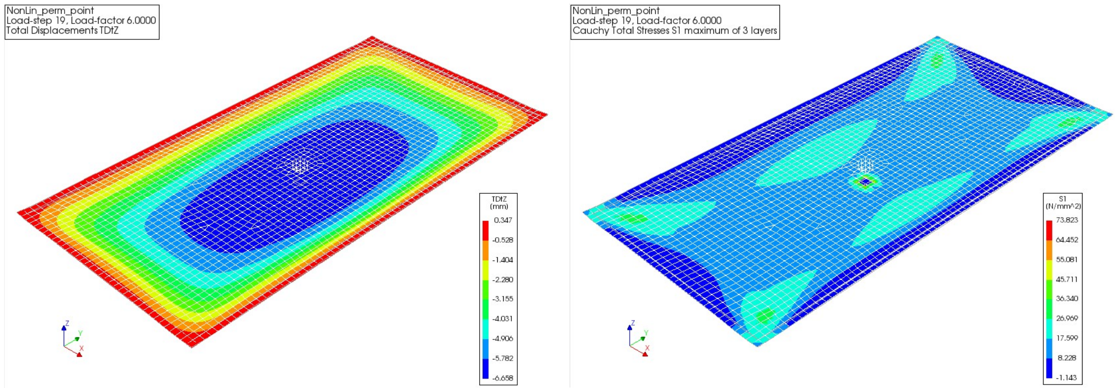
### Rib




**(a)** Max TZ = -3.3 $mm$ **(b)** Max S1 = 41.6 $N/mm^2$

**Figure G.5:** Contour plot load-step 19 non-linear analysis rib variation

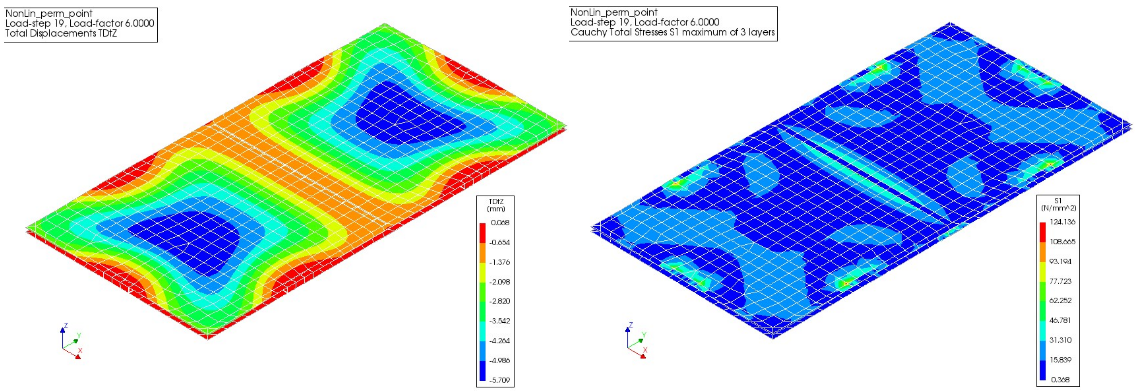
### Cable




**(a)** Max TZ = -6.7 $mm$ **(b)** Max S1 = 73.8 $N/mm^2$

**Figure G.6:** Contour plot load-step 19 non-linear analysis cable variation

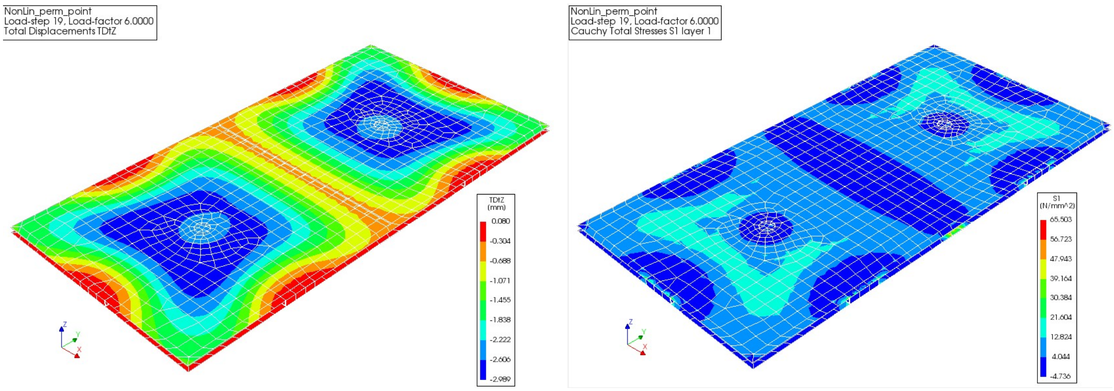
### Sandwich Rib




**(a)** Max TZ = -5.8 $mm$ **(b)** Max S1 = 124.1 $N/mm^2$

**Figure G.7:** Contour plot load-step 19 non-linear analysis sandwich rib variation

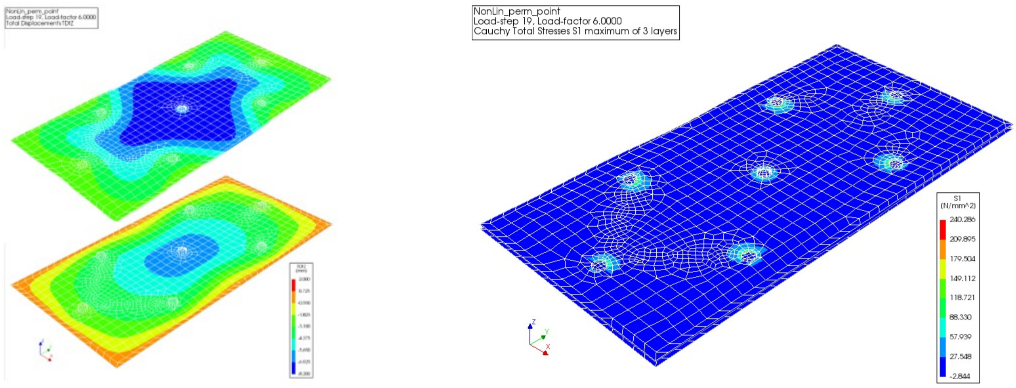
## Sandwich Rib Patch Middle




**(a)** Max TZ = -3.0 $mm$ **(b)** Max S1 = 65.5 $N/mm^2$

**Figure G.8:** Contour plot load-step 19 non-linear analysis sandwich rib patch variation

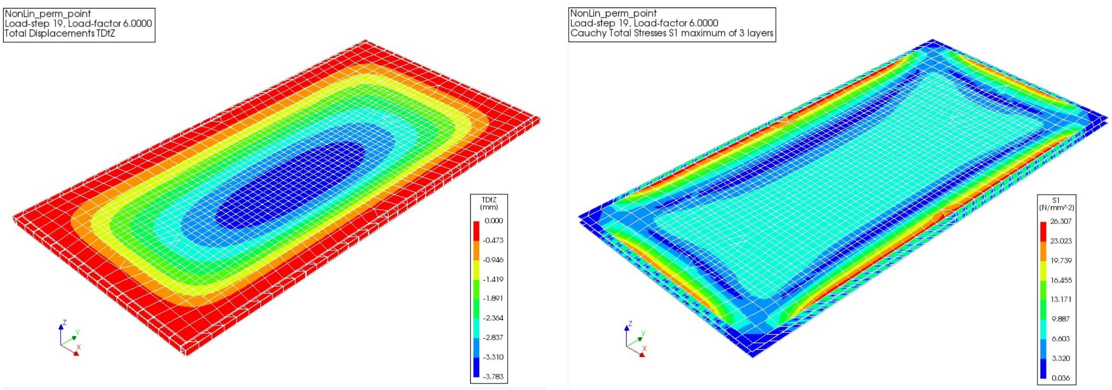
## Sandwich TSSA




**(a)** Max TZ = -8.0 $mm$ **(b)** Max S1 = 240.3 $N/mm^2$

**Figure G.9:** Contour plot load-step 19 non-linear analysis sandwich TSSA variation

## IGU




**(a)** Max TZ = -3.8 $mm$ **(b)** Max S1 = 26.3 $N/mm^2$

**Figure G.10:** Contour plot load-step 19 non-linear analysis insulated glass panel

# G.2. Numerical and Experimental Results: Load-displacement Graphs

## G.2.1. Simply Supported Plate

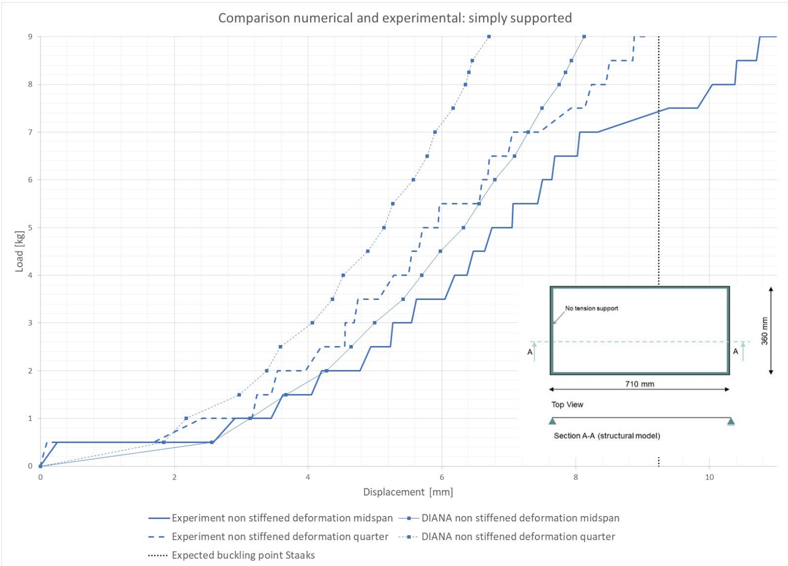



**Figure G.11:** Resulting graph of the displacements at midspan and a quarter for the executed simply supported experiment and the related FE model

Conclusion is that the results of the FE model are comparable to the results of the experiment. However, no out-of-plane behaviour is present in the FE model.

## G.2.2. Single Plate Fixed Supports

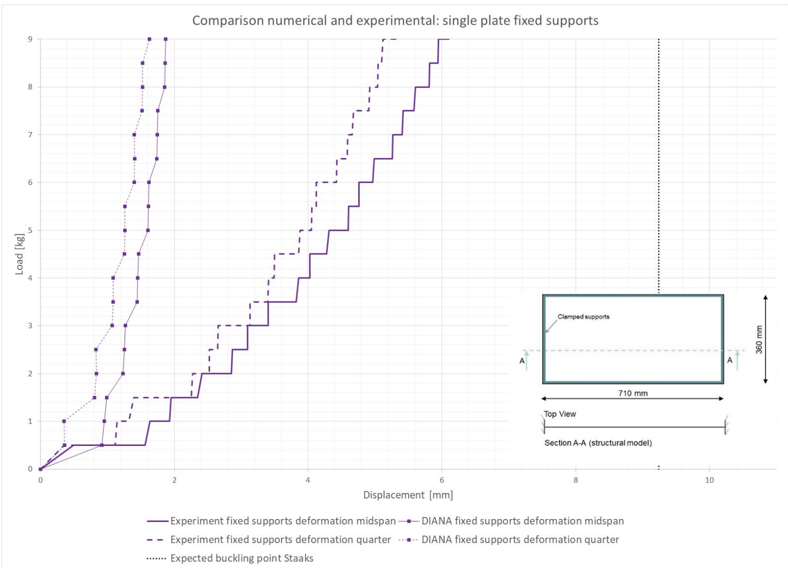



**Figure G.12:** Resulting graph of the displacements at midspan and a quarter for the executed single plate with fixed edges experiment and the related FE model

Conclusion is that there is a difference between the results of the numerical and experimental analysis. This is likely to be caused by the fact that no fully fixed supports are realised during the experiment. Slipping and small deformations of the panel at the edges can cause the higher deflections of the experiment than predicted with the FE model in which the edges can't move.

## G.2.3. Single Plate Rib Stiffener

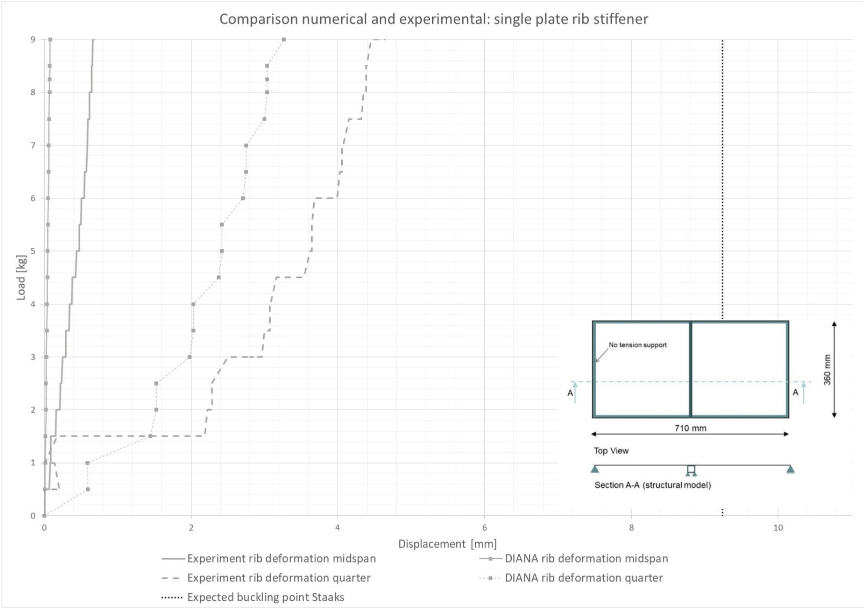



**Figure G.13:** Resulting graph of the displacements at midspan and a quarter for the executed single plate with rib stiffener experiment and the related FE model

Conclusion is that there is a difference between the results of the numerical and experimental analysis. This is probably caused by small deformations of the rib supports during the experiment, while these are completely fixed in z direction for the FE model.

## G.2.4. Single Plate Cable Stiffener

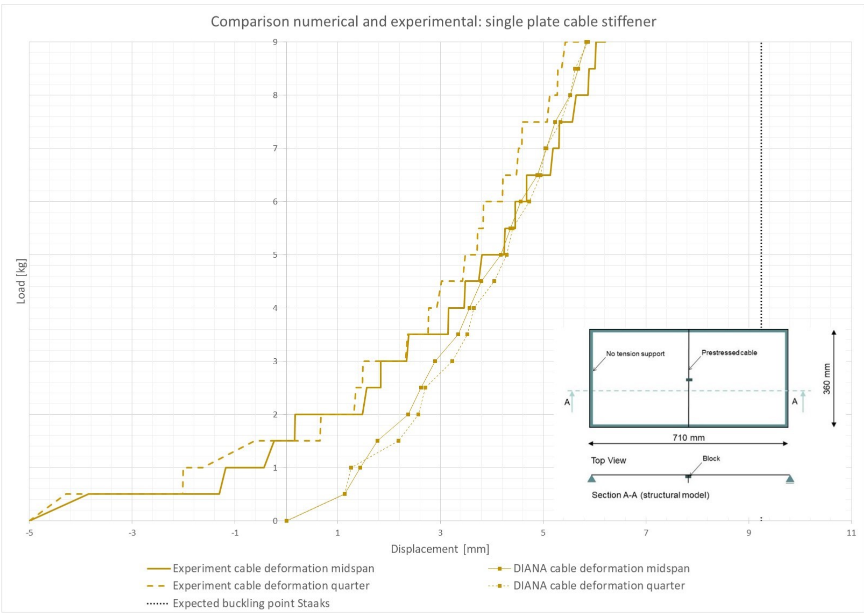



**Figure G.14:** Resulting graph of the displacements at midspan and a quarter for the executed single plate with cable stiffener experiment and the related FE model

Conclusion is that the results of the FE model are comparable to the results of the experiment. However, the difference at the beginning of the load application can be explained by the fact that an initial curvature caused by the pre-tensioned cable is present in the experiment while this was not present in the FE model.

## G.2.5. Sandwich Plate Box Sections

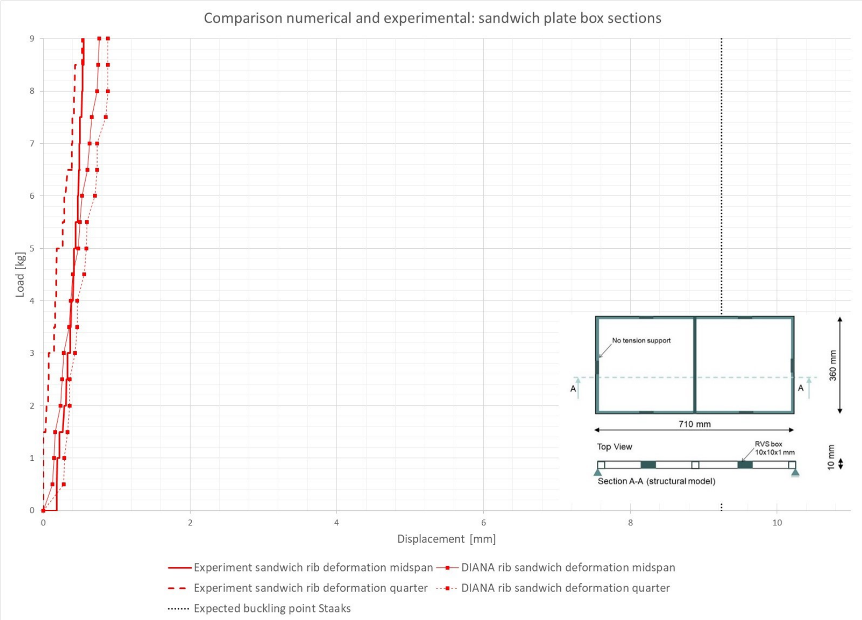



**Figure G.15:** Resulting graph of the displacements at midspan and a quarter for the executed sandwich with rib stiffeners experiment and the related FE model

Conclusion is that the results of the FE model are comparable to the results of the experiment.

## G.2.6. Sandwich Plate Box Sections and Patches

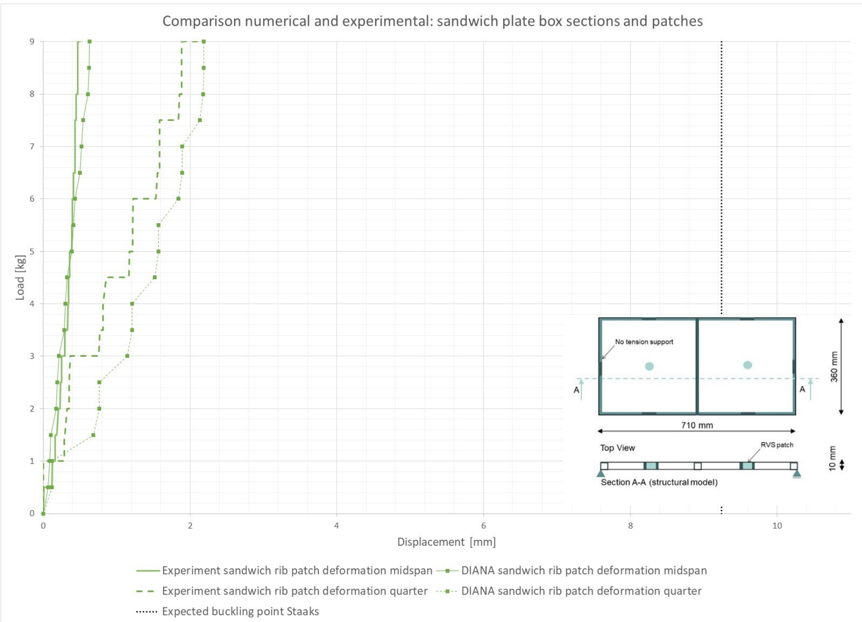



**Figure G.16:** Resulting graph of the displacements at midspan and a quarter for the executed sandwich with rib stiffeners and patches experiment and the related FE model

Conclusion is that the results of the FE model are comparable to the results of the experiment.

### G.2.7. Insulated Glass Unit

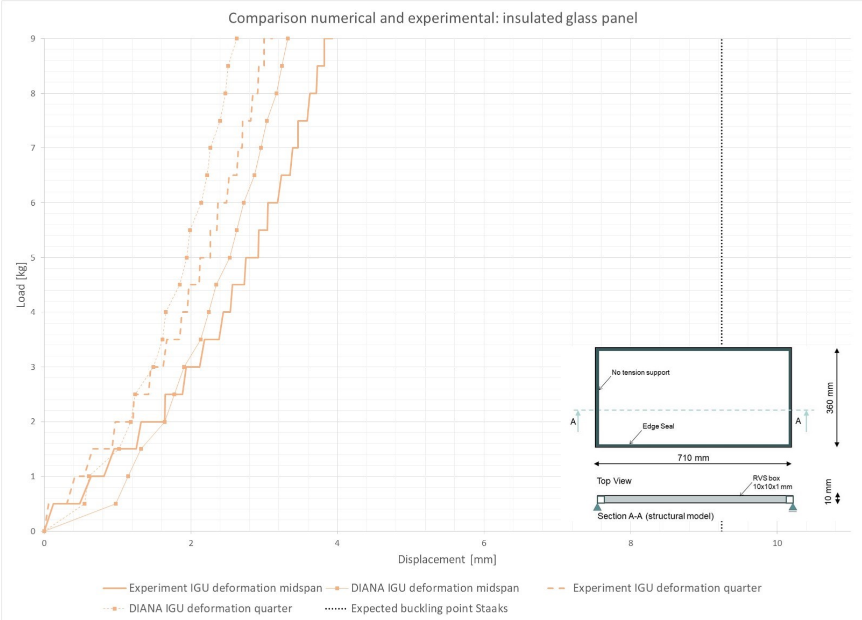



**Figure G.17:** Resulting graph of the displacements at midspan and a quarter for the executed insulated glass unit experiment and the related FE model

Conclusion is that a small difference is present between the results of the numerical and experimental analysis. This difference can be explained by the fact that the edges of the IGU panel during the experiment were not completely straight while a completely flat IGU panel was assumed for the FE model. However, in general it can be concluded that the results of the FE model are comparable to the results of the experiment.

### G.2.8. Total Comparison Numerical and Experimental Results

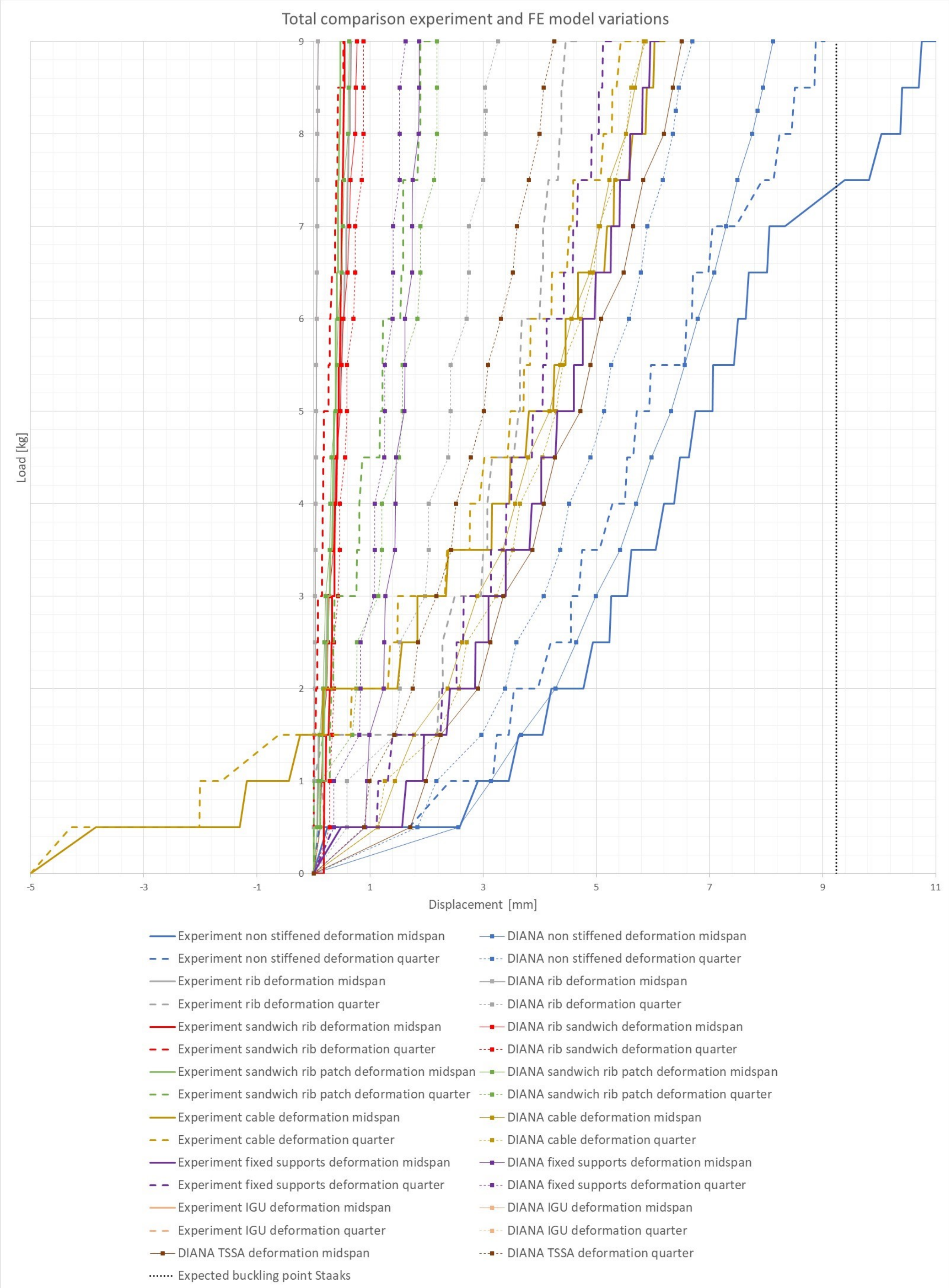



**Figure G.18:** Resulting graph of the displacements at midspan and a quarter for the all executed experiments and the related FE models