ACKNOWLEDGEMENTS

Proudly I present my graduation thesis which I have enjoyed working on for approximately one year. The subject of this graduation thesis is an innovative structural element: load bearing glass columns. As part of the academic curriculum at Eindhoven University of Technology, I worked on another experimental research project about an innovative flexible formwork system. During this research project the innovative nature of the subject fascinated me and to do experimental research and finding explanations for the events observed during the experiments appealed to me. To do an experimental research on an innovative structural system for my graduation project was a chance to work at a more extensive research project.

The use of glass as a structural material always fascinated me. Glass is a material which appeals to me and a lot of architects and structural designers because it is contradicting properties: for instance the possibilities as a structural material, although it glass is transparent. My interest on this subject was even more triggered by an excursion arranged by study association KOers in March 2012. An experimental research project in structural glass was therefore an obvious choice for my graduation project.

Writing this graduation thesis would not have been possible without sufficient support from my environment. First of all, I would like to express my gratitude to the members of my graduation committee prof. Dr.-Ing. Patrick Teuffel, ir. Gerald Lindner (Eindhoven University of Technology) and Prof.ir. Rob Nijsse (ABT bv and Delft University of Technology). I profoundly appreciate their support, critical notes, valuable remarks and suggestions throughout the duration of this project. Furthermore I would like to thank Dr.ir. Fred Veer (Delft University of Technology) for his support during my graduation project, especially with respect to the numerical research.

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Last but not least I would like to thank my friends and family, especially my parents Jan van Heugten and Anita van Heugten-Smits and my girlfriend Nicole Manders for their encouraging talks and their interest, motivation and stimulation during my graduation project and the entire period of my study.

Roy van Heugten
Neerkant, oktober 2013
### SUMMARY

Glass has been used to enclose space and give shelter for ages, but in the past it was merely used as an infill-material rather than a load-bearing material. In contemporary architecture, glass has acquired its significance as a structural building material. Nowadays, all structural members can be created out of glass, but the load-bearing glass column is still in its early phases of design compared to the other structural elements.

In ‘Part 1 – literature overview’ various concepts for load-bearing glass columns are discussed. From these concepts, the stacked column is selected for further research: first of all because knowledge on this type of column is less developed. This concept might also be an ideal way to make use of the high (theoretical) compression strength of glass: the loads can be introduced in the center of the glass panels, rather than on the edges. And because the strength of the center is substantially larger than the strength of the edges of glass panels, the load-bearing capacity of a stacked column is expected to be relatively large compared to the other concepts for load-bearing glass columns. Furthermore the architectural possibilities by means of waterjet abrasive cutting techniques are virtually endless and therefore columns of any shape and appearance belong to the possibilities.

In ‘Part 2 – the stacked column’, the load-bearing capacity of a stacked column is analysed. Important aspects, regarding the load-bearing capacity, are the material glass itself, the load-introduction and the stabilizing strategy of a stacked column. These three aspects are analysed by means of experimental and numerical research.

### GLASS

Plain float glass is used for the experiments and all the edges are ground and polished to reduce micro-cracks, resulting from the cutting of the panels, to a minimum. From measurements on the tolerances on the thickness of these panels it can be concluded that these tolerances are critical for the concept of stacking when larger sheets of glass are used (even when the column is stabilized by means of an adhesive interlayer): 95% of the glass panels will have (at any given point) a thickness between 11,646 mm and 11,880 mm, which is a relatively large range. These tolerances, however, can easily be minimized by cutting glass panels for the column only out of the center of the large sheets resulting from the production process. The measurements on the flatness of the float glass panels are not critical: 95% of the total deviation from the flat surface will be between \(-0,026\) and \(+0,026\) mm, which is a relatively small range.

### LOAD-INTRODUCTION

As for the load-introduction into a stacked glass column, different intermediary materials are analysed by means of experimental and numerical research: steel, rubber, POM, nylon and aluminium. The function of the intermediary is to introduce the loads, coming from other building components, into the glass column in such a way that stress concentrations and tension forces do not occur in the top/bottom glass panels.

From the experimental research, with a single glass panel between two specimens of the intermediary material, and the numerical research, it can be concluded that steel, surprisingly, is the most promising intermediary material. Statistical interpretation of five ‘identical’ experiments resulted in a characteristic initial crack stress of \(-209,8 \text{ N/mm}^2\) for steel. The characteristic initial crack stress for steel is twice as high as for aluminium and approximately 10 to 20 times as high as for nylon, rubber and POM.
These results can be explained by the presence of horizontal compressive forces in the glass panels because of the steel intermediary: due to the high Young’s modulus of steel, the transverse deformations of the steel intermediary are smaller than the transverse deformations of the glass panel. Subsequently horizontal compression forces are introduced in the glass panel, due to friction between the surfaces of the two materials. For the other materials the transverse deformations of the intermediary are larger than the transverse deformations of the glass panels, which introduces horizontal tension forces in the glass specimen, causing the panel to break at much lower stresses.

**STABILIZING STRATEGY**

This graduation project focuses on the stabilizing strategy by means of an adhesive interlayer. This stabilizing strategy is the only one, which is able to slow down/stop crack growth and prevent shards of glass from flying around, by means of the adhesive interlayer between the glass panels. As for the other stabilizing strategies nothing prevents shards of glass from flying around, which leads to unsafe situations. Three series of experiments are conducted to give insight into the behaviour of the adhesive interlayer under compression loads. From all the adhesive interlayers analysed in the experiments, epoxy adhesive Delo AD821 proves to be the most promising type of adhesive. The most promising characteristic properties can be categorized for three aspects: strength, stiffness and stability of the stacked glass column.

**Strength:**

From the results of the experiments it can be concluded that by means of an adhesive interlayer a higher characteristic initial crack stress can be achieved, compared to a dry stack (i.e. without an adhesive interlayer).

The characteristic initial crack stress is highly dependent on the properties of the adhesive interlayer and the Young’s modulus is the most important property. From the results of the experiments it can be concluded that an adhesive with a low Young’s modulus is the most suitable, because it is able to redistribute the loads over a greater surface, and thereby reducing stress concentrations.

Liquid applications of adhesives prove to be able to slow down/stop crack growth, so an initial crack does not immediately lead to ultimate failure of the column, whereas adhesive films are not able to slow down crack growth. This can be explained by the fact that a liquid adhesive, contrary to the adhesive film, cures and forms a strong (chemical) bond with the glass panels and subsequently is able to withstand tension-forces (to some degree). Stacked columns, stabilized by means of a liquid adhesive interlayer, therefore have a relatively large post-initial crack strength, which leads to a safe failure-behaviour: lots of cracks are visible before the column collapses, so people can be evacuated and precautions can be made to prevent the column from collapsing.

**Stiffness:**

The total axial deformations should not be too large, because when the top point of the columns lowers too much, it is not able to act as a bearing for the other structural elements which are connected to the column. From the results of the experiments it can be concluded that the thickness of the adhesive interlayer plays the most important role and should be minimized.
Stability:
The stacked columns used in the experiments had a relatively low slenderness (i.e. slenderness <8) and columns with such a slenderness are not expected to be susceptible for (Euler) buckling. So no research has been conducted into (Euler) buckling of stacked columns. However, during the last experiment the center of the large stack with an adhesive film as an interlayer swayed to the left. Although this is not (Euler) buckling in the traditional sense of the phenomenon, this observation points to instability problems. In this case it’s more like a central glass panel is pushed out of the layered column due to horizontal forces. An adhesive film does not cure and does not form a strong (chemical) bond with the glass panels and thus the column appears as a layered element. A liquid adhesive does cure and does form a strong (chemical) bond which results in a more or less solid element. From this it can be concluded that stacked glass columns with adhesive films as an interlayer are more susceptible for instability problems.

OVERALL CONCLUSION
The most promising stacked column (i.e. with steel as an intermediary and epoxy adhesive Delo AD821 as an adhesive interlayer) of twenty glass panels had an initial crack stress of -108,1 N/mm² and an ultimate failure stress of -190,3 N/mm². Compared to the failure stresses of other concepts of glass columns the failure stresses for the stacked column are 3 to 9 times higher. Compared to the compressive strengths of other building materials, the failure stresses for stacked column prove to be higher than the compressive strengths of concrete and timber.

These failure stresses for the stacked column of twenty glass panels, however, result from a single experiment, so the characteristic failure stresses will be lower. For the stacked column of five glass panels characteristic failure stresses were calculated by means of statistical interpretation of five ‘identical’ experiments. The characteristic initial crack stress is -101,0 N/mm² and the ultimate failure stress is – 217,1 N/mm². These characteristic failure stresses are also higher than the compressive strengths of concrete and timber.

From the viewpoint of material failure, it can be concluded that stacked glass columns are structurally feasible. Additional research should be conducted into the behaviour of stacked glass panels for buckling, fire-resistance, impact loads, long-term loading, environmental influences etc.
# LIST OF SYMBOLS AND ABBREVIATIONS

## Symbols

### Latin capital letters:
- **C**: Spring stiffness
- **C\text{glass}**: Spring stiffness of glass
- **C\text{intermediary}**: Spring stiffness of the intermediary
- **C\text{tot}**: Total spring stiffness
- **E**: Young’s modulus
- **F**: Force
- **F_1**: Initial crack load
- **F_f**: Friction force
- **F_{k,1}**: Characteristic initial crack load
- **F_{k,2}**: Characteristic second crack load
- **F_{k,3}**: Characteristic third crack load
- **F_{k,ad}**: Characteristic load for a certain axial deformation
- **F_{k,u}**: Characteristic ultimate failure load
- **F_u**: Ultimate strength
- **L**: Original length
- **L_{c,1}**: Initial crack length
- **\nu_x**: Coefficient of variation of X
- **\bar{X}**: Sample mean
- **X_k**: Characteristic value of a material property

### Latin lower case letters:
- **g**: Gravitational acceleration
- **k_n**: Characteristic fractile factor
- **m**: Mass
- **m_x**: Mean of n sample results
- **m_{k,1}**: Mean initial crack load
- **m_{k,2}**: Mean second crack load
- **m_{k,3}**: Mean third crack load
- **m_{k,axial,add}**: Mean load for a certain additional axial deformation
- **m_{k,axial,ini}**: Mean load for a certain initial axial deformation
- **m_{u}**: Mean ultimate failure load
- **s_x**: Sample standard deviation
- **s_{k,1}**: Standard deviation initial crack
- **s_{k,2}**: Standard deviation second crack
- **s_{k,3}**: Standard deviation third crack
- **s_{k,axial,add}**: Standard deviation for a certain additional axial deformation
- **s_{k,axial,ini}**: Standard deviation for a certain initial axial deformation
- **s_{u}**: Standard deviation ultimate failure
**Greek capital letters**

- $\Delta L$: Elongation/shortening
- $\Delta L_{\text{axial}}$: Axial deformation
- $\Delta L_{k,\text{axial,add}}$: Characteristic value of the additional axial deformation
- $\Delta L_{k,\text{axial,ini}}$: Characteristic value of the initial axial deformation
- $\Delta L_{\text{transverse}}$: Transverse deformation

**Greek lower case letters:**

- $\varepsilon$: Strain
- $\eta_k$: Characteristic value of the conversion factor
- $\mu$: Coefficient of static friction
- $\nu$: Poisson Ratio
- $\sigma$: Stress
- $\sigma_{k,1}$: Characteristic initial crack stress
- $\sigma_{k,2}$: Characteristic second crack stress
- $\sigma_{k,3}$: Characteristic third crack stress
- $\sigma_{k,ad}$: Characteristic stress for a certain axial deformation
- $\sigma_{k,\text{ui}}$: Characteristic ultimate failure stress
- $\varphi$: Angle of inclination

**Abbreviations**

- 468MP: 3M adhesive transfer tape 468MP
- A5010: Akemi Akepox 5010
- AA: Anaerobic
- AC: Acrylic/Acrylate
- AD821: Delo Duopox AD821
- AF: Acrylic film
- AFTC: Acrylic Foam Tape Company
- CA: Cyanoacrylates
- CTM: Compression testing machine
- DP610: Scotch-Weld DP610
- EP: Epoxy
- IM: Imides
- P4302: Delo Photobond 4302
- P4468: Delo Photobond 4468
- PA-6: Polyamide
- PE: Polyester
- PH: Phenolic
- POM-C: Polyoxymethylene
- PU: Polyurethane
- PVA: Polyvinylacetate
- SCALP: Scattered light polariscope
- SI: Silicone
- ST8502: AFTC Silvertape 8502
- THM: Thermoplastic hot melt
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PART 2:
THE STACKED COLUMN
Chapter 1:
INTRODUCTION ON
THE STACKED COLUMN
1 INTRODUCTION INTO THE STACKED COLUMN

The concept of stacking glass panels is not entirely new. Well-known artists and sculptors all over the world have used this technique to make amazing pieces of art. These sculptures combine the tactile qualities of glass and the unique ability of glass to transform light and at the same time exploiting the strength of glass under compression. These sculptures combine feats of design and engineering to produce artwork, breath-taking in its simplicity (fig. 1.1).

These sculptures have inspired architects in some cases to use the concept of stacking in a handful of building projects. Small stacked building components are incorporated in the building skin of these projects. However the concept of stacking glass could exploit the structural possibilities of glass, the building components were used as an infill material, rather than a structural component. The next step would be to use these elements as load-bearing walls or columns. But to do this, a lot of research into stacked structures is necessary. In this graduation project some research is conducted into some of the aspects involved with the stacking of glass structures. In ‘part 1 – literature overview’ some projects with stacked sculptures are discussed and specific points of attention came to light: the architectural possibilities, the stabilizing system and the tolerances on thickness and flatness. These points of attention and the load-bearing capacity of the stacked column are extensively discussed and analysed in the upcoming paragraphs and chapters.
1.1 Architectural possibilities

Glass is often used to create a ‘dematerialized’ building skin, resulting in a complex system of glass and fixings. In contrast, stacking is a simple construction principle similar to monolithic construction. While structural glass façade-systems aim for minimizing the number of components, stacked glass focuses on minimizing the number of different components (to reduce the production costs). Even with a small amount of different components lots of different shapes are possible. Form-finding is determined by the size and shape of the basic element and the principle of arranging the elements.

With identical basic elements, different overall shapes of the column are possible by translating or rotating the elements with respect to each other (fig. 1.2). When translation and rotation are combined the number of possible shapes become even greater. The load-bearing capacity of the column depends largely on the shape of the column: compression forces will be transferred from panel to panel and therefore the panels should have a large overlap. Although the translations/rotations between two panels might be small, the total translation/rotation will be large, because a large amount of stacked panels is necessary to construct a column. The total translation/rotation should be limited (especially for ‘linear elements’) resulting in an ‘effective area’ where the compression forces can be directly transferred to the foot of the column. The remaining area of the column will contribute to the load-bearing capacity, but the contribution is limited because of the resulting bending moments.
It is also possible to make variations in the shape and size of the basic elements. Because of the transparent nature of glass a distinction can be made in the outer shape of the panels and the inner shape (fig. 1.2 bottom).

Variations in the outer shape of the elements can result in all kind of different shapes and appearances. This is not only relevant for stacked glass columns but for all stacked structures: the 3D-columns in figure 1.3 are made by Michael Hansmeyer out of stacked cardboard sheets with different sizes and shapes. These columns clearly illustrate the possibilities of stacked structures, which can consist out of stacked glass panes.

It is also possible to design hollow structures by making variations in the inner shape of the basic element. Architects/sculptors could even go a step further and create structures within these structures by making variations in the inner shape as well as the outer shape of the structure. Architects love the way that glass plays with light. With this concept architects can control the way glass plays with light: the amount of transparency (or translucency) can be controlled by varying the distance between the inner shape and the outer shape of the basic elements. The larger the thickness, the more the light will be captured and the less transparent that part of the column will be. Architects can hereby personalize the appearance of the columns completely. For clients the personalisation of the columns could also result in interesting structures: it would, for instance, be possible to incorporate the logo of the company in the column.

Glass furthermore is a material with an enormous richness in treatment: etching, colouring, sandblasting, polishing to name just a few. The edges of the glass panels could also be treated in a lot of different ways from standard edgework like flat polished/ground edges to decorative edgework like waterfall edges etc.

All the options described above (differences in arrangement of identical shaped elements, differences in the shape and size of the elements and differences in colour, texture, edge treatment) of course could be combined as well. It hereby becomes evident that the architectural possibilities of this concept are virtually endless. To illustrate the architectural possibilities two demonstration-models are designed and built (fig 1.4). In Appendix A the design and production process are briefly discussed and some photo’s of the demonstration-models are presented.
1.2 Stabilizing strategy

In part 1 – literature overview three possibilities for the stabilizing system of the column were presented: connection of the individual sheets with some kind of adhesive interlayer; stabilizing the dry structure by superimposed loads or by making a mechanical connection (fig. 1.5).

For the adhesive interlayer all kinds of glue, tape, laminating foils etc. could be chosen. A positive effect of this interlayer is that it is able to redistribute the load over a greater surface avoiding stress concentrations imposed by the variations in thickness and flatness of the glass panels. A negative effect is the flow of the interlayer. With thick interlayers like resin, Polyvinyl Butyral-foil (PVB), etc. and even with thin compressible layers the flow of the interlayers under compression loads has to be carefully considered. The behaviour of these interlayers and also the degradation over time is unknown but has to be taken into account.

Superimposed loads can be introduced by additional dead-load (e.g. by heavy objects placed on top of the stack) or by post-tensioning the stack with the use of tension rods. Post tensioning introduces compression forces in the glass columns which reduces the capacity for the additional compression forces in the load-bearing column. Furthermore, if the stacked structure is used as a column, heavy objects placed on top of the stack are naturally present. Calculations are necessary to prove that the minimal compression force needed to stabilize the structure is always present.

Due to imperfections and irregularities some horizontal forces will always be present. In the case of the concept with additional dead-load, the only thing which keeps the individual glass panes from sliding alongside each other is the friction between the two glass panes and nothing prevents the end-points from moving sideways. Therefore, for safety-reasons, this concept becomes unpractical. In case of an interlayer or a tension rod, the sliding of the individual glass panes is more or less prevented. In case of the tension rod the friction between the glass panes is increased because of the pretensioning and the end-points of the column cannot move sideways without elongation of the tension rod. In case of the adhesive interlayer, the interlayer itself can withstand the occurring horizontal forces, providing that the shear-capacity of the interlayer is sufficient.
To prevent the glass panes from sliding alongside each other another option is available. It could be possible to drill one or multiple holes in each of the glass panels, through which ‘mechanical connections’ could be made. These mechanical connections will be visible (like the steel tension rod) because of the transparent nature of glass. This mechanical connection however does not necessarily have to be a steel connection. It could also be a glass bar or tube for instance, which preserves the transparent nature of the column (i.e. more than for a steel connection). In the sculpture of archangel Michael transparent tubes are incorporated in the legs, the body and the wings. In figure 1.6 one could see one of the tubes in the wings on the left hand side of the picture.

COMPARISON FROM DIFFERENT POINTS OF VIEW

Costs
The cheapest solution is the option with no connections (i.e. additional deadload). The option with an adhesive interlayer is the most expensive solution, because of the additional costs for material (adhesives are quite expensive) and production (applying the glue and waiting for it to cure is time consuming and therefore expensive). For the other two options (tension rod and mechanical connection) holes need to be drilled in each pane of glass which is also time consuming and thus will cost money. However, the costs will be lower than the total costs of the adhesive interlayer-concept.

Aesthetics
From an aesthetic point of view it would be nice if the connections between the individual glass panes would not be visible at all. This would clearly be the case when no connections are made and the stability of the column is achieved by additional dead-load on top of the column. But for safety-concerns discussed previously this concept will be unpractical. If the connection between the individual glass panels is made with a transparent interlayer the connection is also practically invisible. The visibility of the interlayer will depend on its thickness: a thick interlayer would be more visible than a thin interlayer.

The other two options (a tension rod and a mechanical connection) will be more visible. This however does not necessarily mean that these solutions are inferior to the other two solutions. Aesthetics is a matter of taste, and some architects might want to make use these connections in the appearance of the columns. Tension rods can be used to create lines in the column (fig. 1.7), and the glass tubes could for instance be made of glass of a different colour, to emphasize these connections. This all comes down to the personal wishes and desires of the architects and/or clients.
Load-bearing capacity
From a structural point of view the solution with a tension rod is undesirable for a column. Due to the pretensioning in the column, the additional load-bearing capacity of the column decreases. Normally it is advisable for connections in glass to make linear connections. Point-connections lead to stress concentration and making holes in glass leads also to unwanted stresses and imperfections in the panels. Therefore ‘mechanical connections’ will also result in a decrease of the load-bearing capacity.

The behaviour of the interlayer is not a well-documented phenomenon. It is possible that stress concentrations, due to variations in thickness and flatness of the glass panels, could be re-distributed because of the interlayer. However, the flow and creep of the interlayer could result in undesired behaviour of the column. Whether the interlayer has a positive or a negative influence on the structural behaviour of the column should be investigated.

Production process
A negative aspect of the concept of the interlayer is the amount of time which is needed for curing of the interlayer. Some adhesives take up a lot of time while curing and other adhesives cure within a couple of minutes. This depends largely on the method of curing. Some glues cure with UV-light as a katalysator, or because of a chemical reaction, or by the atmospheric moisture. Uv-light curing adhesives are generally the fastest curing adhesives. Figure 1.8. shows the curing process with UV-light and the necessary equipment (fig. 1.9). Some adhesive tapes cure ‘instantly’ so this will not take up any time. This aspect is important when a column, consisting out of hundreds of glass panes is produced. For the other concepts the curing-time is not relevant at all (or plays just a minor role).

Another aspect of the production process is the positioning of the individual glass panes. When all the individual glass panes are of identical size and shape, the positioning is not that difficult. When the sizes and shapes differ between the individual glass panes the position with respect to each other becomes important. In the concepts of the tension rod and the mechanical fixing, holes are present at the exact same location for each individual glass panel. These panels could therefore be positioned using these holes. In the concepts of the interlayer and additional dead-load, no holes are present which makes the alignment of the panels considerably harder.
Safety
When the column fails, this should not lead to dangerous situations. When buckling of the column is prevented (i.e. the slenderness is sufficiently low), the column will fail when the crack-growth cannot be controlled anymore. When these cracks occur precautions should be made to prevent shards of glass from flying around. The stabilizing system with the interlayer is the only concept where the entire surfaces of the glass panels are connected to each other. The interlayer can slow down/stop the crack-growth and makes sure the shards of glass will not fly around. This aspect should be considered for the other concepts, because nothing prevents shard of glass from flying around.

Disassembly
The option with additional dead-load, and the tension rod-concept, will be quite easy to disassemble and recycle, because the panels are not connected to each other or the connection can be easily undone (i.e. by removing the tension force). When the panels are glued together with an interlayer, or when a mechanical connection is glued to the glass panes, the disassembly becomes a lot harder.

Conclusion
An adhesive interlayer is a promising stabilizing strategy but the behaviour of an adhesive interlayer under compression is unknown. This plays an important part in the choice for a stabilizing strategy and therefore this will be the focus of some series of experiments in chapter 3 - 6. After these experiments it should be clear if an adhesive interlayer is a promising option for stabilizing the column and which kind of adhesive interlayer will be suitable.
1.3 Tolerances

When glass panels are stacked to create load-bearing structures the tolerances on the thickness and flatness of the individual glass panes need to be considered (fig. 1.10). This subject is analysed by Jan Wurm [1] and has already been discussed in part 1 – literature overview. The conclusions are summarized below:

The tolerances on thickness given in BS EN 572-2:2004 appear typically in a float glass cut across the ribbon. These tolerances can lead to stresses which exceed the allowable stresses of tempered glass and thus are critical for the concept of stacking. In order to avoid these tolerances, glass from the center of the sheets needs to be used, where the deviations from the nominal thickness are smaller by a factor of 10.

The tolerances on the flatness, (i.e. local and overall bow) seem to be less critical. The local bow with a maximum of 0.5 mm/300 mm (EN 12150-1:2000) is only locally present and the probability of this variation occurring on the exact same location in the stack is low. The overall bow is typically limited by industry standards to 0.1% of the long edge and the dead-load of the panels will level itself when stacked up, therefore avoiding any stress concentrations.

Roller waves, introduced during the toughening process, can vary ca. between 0.01 mm and 0.3 mm. The effects of the roller waves prove to be quite substantial and need to be minimized as much as possible. For this reason toughened glass is less suitable, especially for dry stacked structures.

An interlayer could be able to (partly) reduce the effects of the tolerances, depending on its thickness. A thick interlayer would be needed to reduce these effects almost entirely. This however is contradicting with the desires of a thin, invisible interlayer, of which the flow and creep of the interlayer under compression is limited.
1.4 Load-bearing capacity

The load-bearing capacity of a dry stacked glass column is not well-documented, Neither is the behaviour of an adhesive interlayer in a stacked glass column. To gain insight in these aspects experimental research would be necessary. In the upcoming chapters the experimental research, which is conducted for this graduation project, will be discussed.
Load-bearing capacity
PART 2.1:
EXPERIMENTAL RESEARCH
THE STACKED COLUMN
Chapter 2:
INTRODUCTION ON EXPERIMENTAL RESEARCH
2.1 Overview of the experiments

The first issue which comes to mind is how the forces should be introduced in the glass panels. In glass-connections it is normally advisable to avoid direct contact between steel and glass and to introduce the forces through an intermediary material. Experimental research into the behaviour of intermediary materials is the subject of the first series of experiments. Different kinds of intermediary materials will be used during the experiments and compared (fig. 2.1).

The other series of experiments will be into the behaviour of stacked ‘column’ with an adhesive interlayer between the glass panels. An adhesive interlayer is one of the stabilizing strategies, discussed in paragraph 1.2.

For the second series of experiments two glass panels are connected with 7 different types of adhesives and adhesive films, both with various properties. This should result in some insight into the behaviour of and important properties for an adhesive interlayer.

Depending on the results of the second series of experiments, four types of adhesive interlayers will be selected for the third series of experiments. In these experiments the behaviour of a small stack of five glass panels, subjected to compressive loads, will be analysed.

Finally two experiments will be conducted on a large stack of 20 glass panels, connected with two types of adhesive to see if the behaviour of this large stack differs from the behaviour of the small stacks. The standard deviation of the strength of glass panels is quite large. Therefore the load-bearing capacity of one panel differs from another panel. The column is only as strong as the
weakest ‘link’ in the column, so if this plays a role the load-bearing capacity of the large stack should statistically be smaller than the small stack. Furthermore it would be interesting to analyse how the cracks propagate through the specimen. Will the cracks concentrate in one or multiple adjoining glass panels which results in total failure of these panels, while the other panels remain intact? Or will small cracks occur in all the glass panels, before one or multiple panels will fail totally?

2.1.1 Overall test setup
The load-bearing capacity (i.e. compressive strength) of the stacked glass column, with and without an interlayer, can be measured with a compression testing machine (CTM). These machines are often used to measure the compressive strength of concrete cubes or cylinders, but could also be used for measuring the compressive strength of glass. The concept of the compressive strength test setup is visualized in figure 2.2. In-between the upper and lower part of CTM two steel cubes where placed. The only function of these cubes is to get a clearer view on the glass-specimens. The dimensions of the specimens are smaller than the area of the upper and lower part of the CTM. Furthermore the thickness of the glass is quite small, and therefore the view on the specimens would be bad without these steel cubes. Special care has been taken to make sure that the surfaces of the steel cubes are ‘totally’ flat (by use of a milling machine) and that the top and bottom plane are parallel to each other. Between these two steel cubes the actual test-specimens will be placed. From paragraph 2.1 it became clear that the actual test-specimen can range from a single glass panel with different intermediary materials, to a large stack of 20 glass panels connected with one type of adhesive.

The test-specimens are loaded by a CTM (type:Alpha1-4000, Form+Test Prüfsystemel) with a capacity of 4MN. The experiments are conducted at a constant load rate of 5 kN/s and the resulting displacement has been measured every second by the internal measurement-equipment of the CTM.
Polarizer-films are used to determine the exact moment that the first crack occurred. Stresses in transparent objects can be visualized with help of these polarizer-films. The concept of these films is illustrated in figure 2.3.

The nature of light can be described both as a particle and as a wave. If we imagine light as a wave, normal, unpolarized light is a wave which vibrates in all directions. When light is sent through a linear polarizer, the light becomes polarized which means that it only vibrates in one direction. The direction of the vibration depends on the direction of the linear polarizer. When this linear polarized light is send through another linear polarizer which is rotated 90° all the light is blocked. This is illustrated in the upper part of figure 2.3. [2]

Transparent objects, like glass, are known to refract light. In glass normally there is only one index of refraction. But when a force is acting on the glass, the glass is deformed and the index of refraction changes. Therefore the refractive index depends on the internal stress in the glass object. When this glass object is placed between two polarizer films (where one is rotated 90° compared to the other) the linear polarized light becomes unpolarized due to the different refractive indexes in different locations of the glass (depending on the stress). Therefore some light will pass through the second polarizer film and the stresses in the glass can be visualized and measured (fig. 2.3 - bottom). The visualization is only qualitative: relative differences in stress at different positions can be visualized, but the amount of stress is not known. It furthermore is not possible to distinguish compressive stresses from tensile stresses. When a crack occurs in the glass object, the internal stress in the glass object instantaneously changes and therefore the refractive index changes also. That is why the occurrence of the first crack can clearly be visualized with help of the polarizer-films.
2.1.2 Glass

DIMENSIONS
For the experiments float glass is used with dimensions of 100x100x12 [mm]. The compressive (crushing) strength of glass is not a well-documented value but in some literature it is found to be 325 N/mm². [3] Dimensions of 100x100mm will result in a total load of 3,25 MN, which is within the capacity of the CTM. A thickness of 12mm is used because this is the largest thickness, which is easily available. Panels with a thickness of 15 mm or 19mm are also available, but not as standard as 10mm or 12mm.

TYPE OF GLASS
Toughened glass would be able to withstand higher tensile stresses which can occur due to irregularities or defects in the glass or on the surface of the glass. However, when toughened glass is used, an initial crack will result in immediate failure of the entire panel. When toughened glass is used in a dry stack, the shards of glass will fly around everywhere which leads to unsafe situations. An adhesive interlayer will make sure that the shards of glass will not fly around, but the entire panel will still be cracked. This and the presence of the roller waves in toughened glass (paragraph 1.3), leads to the choice of float glass for the experiments.

EDGE TREATMENT
The strength of glass often depends on the edge treatment. Edges which are not treated after cutting are full of micro-cracks (so called Griffith flaws) which seriously decreases the strength of glass [4]. In compression these micro-cracks are closed and their effect on the strength is limited. In tension, on the other hand, these micro-cracks are weak points which easily can become a large crack. When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression. This phenomenon is called the Poisson effect and leads to tensile stresses in the directions perpendicular to the applied load. Therefore a compression test will also lead to tension stresses and subsequently the edge treatment is of importance. When the edges are ground and polished the micro-cracks are reduced to a minimum and the resulting strength of the glass will be higher. For this reason ground and polished float glass is used for the experiments.

Waterjet-abraded glass panels would also be an option, but this option is more expensive. In practice the importance of waterjet-abraded glass panels should not be underestimated because with this technique panels can be cut in all kinds of shapes and figures (also hollow shapes) which make the architectural possibilities greater than for ground and polished float glass.
THICKNESS AND FLATNESS

In the beginning of this paragraph the choice for a thickness of 12 mm for the glass panels is discussed. However the thickness will not be exactly 12 mm, which became clear in paragraph 1.3 where the influence of the tolerances on the thickness and flatness of the glass panels was analysed. Whether or not these tolerances play a role in the small-scale specimens is analysed by measuring the flatness and thickness of a sample of the panels which will be used for the experiments. The thickness is measured using a micrometer (Mitutoyo N102-217) and the flatness is measured with a dial test indicator (Mitutoyo 513-204F) in a milling machine. Both measurement devices have an accuracy of or 0,01 mm. The flatness of 12 glass panels is measured (both front and back) and for the thickness 24 panels in total are analysed.

In appendix B an entire overview is given of the setup of the measurements, the results and the analysis of these results. In this paragraph only the conclusions will be discussed.

Thickness

From the measurements of the thickness it can be concluded that 95% of the glass panels will have (at any given point) a thickness between 11,646 mm and 11,880 mm (fig. 2.4). The range of the thickness is relatively large, because the small glass samples are cut from both the center and the edges of large glass sheets, whereas the maximum thickness of the glass sheets always occurs close to the edge.

In this instance it, probably, does not lead to problems because the difference in thickness in one panel of 100 x 100 mm is relatively small: the measured thickness at any given point of the glass panel of 100 x 100 mm is compared to the nominal thickness of that panel. From these measurements it can be concluded that 95% of the deviation from the nominal thickness in one glass panel (at any given point) will be between – 0,016 mm and +0,016 mm (fig. 2.5).

Full-size columns will have (much) larger dimensions than 100 x 100 mm and then the deviation from the nominal thickness in one glass panel can become an issue. To minimize these deviations it is advisable to use glass panels which are cut from the center of the large glass sheets, because the deviations on the thickness are smaller by a factor of 10, compared to the thickness on the edges.
Flatness

The flatness of both the front and the back of the glass panel is measured with a dial test indicator in a milling machine. This results in a series of measurements through which an ‘ideal flat’ surface is calculated with the ‘least squares estimation’-method. The ideal flat surfaces for the front and back differ from each other and are averaged, to get an ideal flat surface per glass specimen. Subsequently, for both the front and the back of the panels, the deviation from this ‘ideal flat’ surface is calculated.

From these calculations it can be concluded that 95% of the deviations for the front of the glass panel from the ‘ideal flat’ surface are within $-0.014$ and $+0.011$ mm (fig. 2.6). For the back of the glass panels the 95%-boundaries are $-0.012$ and $+0.015$ mm. The total deviation from the flat surface will be between $-0.026$ and $+0.026$ mm. The tolerances on the flatness are small and therefore, in all probability, these tolerances will not lead to any problems.

Qualitative analysis

Furthermore the results of the measurements of both the thickness and flatness are visualized in contour plots to analyze if ‘a specific trend’ is visible in the deviations (fig. 2.7 shows an example of such a contour plot for the flatness of the back side of panel 1).

‘A specific trend’ means that it for instance could be the case that the thickness of the center of the glass panel is smaller than the thickness of the edges. Or that the glass panels have an overall bow mainly in one direction, or in both directions. Analysis of all the contour plots (appendix B) does not show a specific trend neither for the flatness nor the thickness.

The flatness and thickness of the small panels depend on the exact it was cut out of the large sheet of glass. Because the small panels are cut from both the center and the edges of a large glass sheets, it can be explained that no specific trend is visible in the flatness and thickness of these panels. Furthermore the deviations from the thickness and the flatness are small and therefore a specific trend would be speculative.
Chapter 3:

EXPERIMENTS A – INTERMEDIARY
3 EXPERIMENTS A – INTERMEDIARY

In Part 1 – Literature overview it became clear that direct contact between glass and steel should be avoided. Because both of the materials are quite hard and stiff, stress concentrations will occur at points of direct contact and at these points cracks will occur at a small overall stress. An intermediary could reduce stress concentrations depending on its (mechanical) properties.

3.1 Intermediary material-specimens

Intermediary materials are not only applied in the case of glass structures. In the world of engineering intermediary materials are often applied in different bearing supports. For example: bridges or earthquake resistant structures sit on top of rubber bearing supports. Hollowcore floors are often supported with felt as an intermediary. In Part 1 – Literature overview different examples of intermediary materials used for glass structures were discussed: Polyoxymethylene (POM) or (soft) aluminium (1050A-O). For the point connectors of the glass façades of the greenhouses at Parc La Vilette nylon has been used as an intermediary material. The choice of an intermediary material, depends on its properties. The relevant properties are mentioned and described below:

Young’s modulus

The higher the Young’s modulus, the stiffer the material. And the stiffer the material the lower the (elastic) strain is at a given force, which means that the material deforms less. To avoid stress concentrations it will be beneficial when the intermediary can deform to ‘mold’ itself to the profile of the glass. The glass has a certain ‘micro-profile’ because of the tolerances in thickness, flatness, etc. which is discussed in paragraph 1.3. In order to deform and adapt to the profile of the glass the Young’s modulus should be lower than the Young’s modulus of glass.

Poisson’s ratio and coefficient of friction

These two mechanical properties combined are of interest in this application. The Poisson’s ratio is the ratio between the transverse strain and the axial strain. When a material is compressed, it expands in the direction perpendicular to the applied load. The higher the Poisson’s ratio the larger this expansion is. The coefficient of friction is a number which states the amount of friction between two materials. The higher the number, the higher the friction is. The coefficient of friction of the different intermediary materials and glass is experimentally determined in Appendix C.
When a material has a large Poisson’s ratio and also a high coefficient of friction, tension forces are introduced in the glass. This is visualized in figure 3.1. Due to the Poisson effect an axial strain leads to a transverse strain. Due to the transverse strain friction will occur between the intermediary material and the glass (also between the intermediary material and the steel test-bench, but this is not as important). These friction forces will subsequently lead to tension forces in the glass. As previously discussed glass has a low tensile strength, so tension in glass should be avoided. The tension force will be small if the Poisson’s ratio of the intermediary is lower, because the transverse strain is then small. But the tension force will also be small if the friction coefficient between the intermediary and the glass is lower. Of course, when both the Poisson’s ratio and the friction coefficient are low, the tension force in the glass is also smaller.

**Hardness and ultimate strength**

The hardness of a material can be described as the amount of resistance a material offers against plastic deformation. This can be important for the same reasons as described for the Young’s modulus. The only difference is that the Young’s modulus deals with the elastic deformation and the hardness deals with the plastic deformation. Whether or not the hardness plays a role therefore depends on the ultimate strength, because this property marks the point where the plastic deformation begins.

**Homogeneity**

Stress concentrations in glass should be avoided at all costs. Therefore it is important that the mechanical properties are equal over the entire volume of the material, thus the material needs to be homogeneous.

From the intermediary materials which are often used (i.e. rubber, felt POM, Nylon and aluminium) felt is a highly inhomogeneous material (because it is made out of fibers) and therefore it will be excluded from the experiments. The other materials all are homogeneous and will be used in the experimental research. The above described (mechanical) properties are summarized in table 3.1 for all the materials. To compare the results the experiments will also be conducted with steel as an ‘intermediary material’ [3, 5, 6, 7, 8, 9, 10, 11, 12, 13]

### Table 3.1 Mechanical properties intermediary materials

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus E [N/mm²]</th>
<th>Poisson’s ratio ν [-]</th>
<th>Coefficient of friction vs. glass μs [-]</th>
<th>Ultimate strength Fu [N/mm²]</th>
<th>Brinell HB [-]</th>
<th>Mohs Scale [-]</th>
<th>Shore A [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>70.000</td>
<td>0,2</td>
<td>0,18 – 0,25</td>
<td>33</td>
<td>&gt;&gt;189</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Steel (s355)</td>
<td>210.000</td>
<td>0,27 – 0,30</td>
<td>0,12 – 0,16</td>
<td>355</td>
<td>146 - 187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber</td>
<td>10 – 100</td>
<td>0,48 – 0,50</td>
<td>0,38 – 0,58</td>
<td>6</td>
<td>&gt;&gt;189</td>
<td>4,5</td>
<td>65</td>
</tr>
<tr>
<td>POM-C</td>
<td>2.600</td>
<td>0,35</td>
<td>0,16 – 0,19</td>
<td>63</td>
<td>135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon (PA6)</td>
<td>3.000/1.000²</td>
<td>0,39</td>
<td>0,12 – 0,16</td>
<td>75</td>
<td>160/70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium (1050A – O)</td>
<td>69.000</td>
<td>0,33</td>
<td>0,16 – 0,25</td>
<td>80</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ The steel specimens were milled to a precise thickness, which results in a totally flat and smooth surface
² first number = conditioned situation, second number = wet situation

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Intermediary material-specimens | 24
3.2 Test setup

Five different intermediary materials are used for these experiments: steel, rubber, POM, nylon and aluminium. These intermediary materials are placed on both sides of a 12 mm thick single float-glass panel with ground and polished edges (fig. 3.2). For steel as an intermediary the steel cubes, which were mentioned in paragraph 2.1.1 are used and have dimensions of 100 x 100 x 60 mm. The dimension of the rubber intermediaries are 100 x 100 x 20 mm and for POM, Nylon and (soft) aluminium a thickness of 5 mm is used (length x width = 100 x 100 mm). The dimensions are summarized in table 3.2.

Five ‘identical’ experiments have been conducted with every intermediary material, to achieve a certain amount of reliability. For the experiments with rubber as an intermediary, every time a new experiment was conducted a new intermediary was used, because the rubber intermediary tore apart during the experiments. For the other intermediary materials the same specimens were used every time a new experiment was conducted. The experiment is stopped at the moment the initial crack in the glass panel occurs, in order to see what the crack pattern is of the glass panel. The moment the initial crack occurs can clearly be determined with help of the polarizer film and the crack pattern can provide information about the stresses in the glass panel.

The stress at which an initial crack occurs is a specific moment which can be used to compare the different intermediary materials. An initial crack however does not necessarily mean the end of the life-cycle of the column: an initial crack does not always lead to total failure of the column. Architects/clients have to decide whether or not cracks should be accepted, provided that the structural safety of the column can be guaranteed.

The goal of these experiments is to determine which of the intermediary materials is the best suitable to introduce the forces into the glass panel, which will result in a high load-bearing capacity of the column.

<table>
<thead>
<tr>
<th>Dimensions [mm]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>100 x 100</td>
</tr>
<tr>
<td>Steel</td>
<td>100 x 100</td>
</tr>
<tr>
<td>Rubber</td>
<td>100 x 100</td>
</tr>
<tr>
<td>POM-C</td>
<td>100 x 100</td>
</tr>
<tr>
<td>Nylon</td>
<td>100 x 100</td>
</tr>
<tr>
<td>Aluminium</td>
<td>100 x 100</td>
</tr>
</tbody>
</table>
3.3 Expectations

From the analysis of the properties ‘soft’ aluminium is probably one of the most promising materials as an intermediary. The Young’s modulus of aluminium is (a little bit) lower than the Young’s modulus of glass (fig. 3.3) and therefore the aluminium can mold itself to the micro-profile of the glass panel.

Aluminium furthermore has a low Poisson’s ratio and an average coefficient of friction. This will probably minimize the tension forces which will be introduced into the glass panel.

The yield strength of aluminium is relatively low and therefore plastic deformation will occur. However, the hardness of this alloy of aluminium is low, so the intermediary will deform quite easily also in the plastic range. For this reason, the material can easily mold itself into the micro-profile of the glass panel.

Rubber is probably one of the least promising materials for this application. The Young’s modulus is small and this property will not lead to problems.

The Poisson’s ratio of rubber, however, is quite large. Combined with a high coefficient of friction this will introduce high tensile stress in the glass panels.

The Brinell hardness of rubber is also large and because of the small yield strength of rubber, this leads to highly unfavorable properties for this application.

Based on the same view on the properties an overall prediction of the intermediary materials from promising to least promising can be made: aluminium – POM – nylon – steel - rubber.
3.4 Results (initial crack)

An entire overview of the experiments and the test results are given in Appendix D. The results of the experiments were quite remarkable: the results did not correspond with the available literature and the expectations. Although in most (if not all) projects direct contact between steel and glass is avoided, steel proved to be the best intermediary in this case (fig. 3.4 and table 3.3). The stress indicated in these figures is the initial crack load divided by the entire surface (100 x 100 mm) as if the stress is identical over the entire surface. This is not entirely true but gives a good indication of the dimensions of the columns versus the loads the column can withstand.

From the other intermediary materials aluminium proved to be the most promising, as expected. POM appeared to be the worst material, but the standard deviation for this material was large and the difference between the first experiment, with a fully intact intermediary, and the following experiments, with the same (slightly damaged) intermediary was large (first experiment 167 N/mm$^2$, other experiments 57 – 87 N/mm$^2$). This leads to believe that for POM the influence of the slightly damaged material is quite large. Rubber was expected to be the least promising material and the differences of the results for the characteristic failure stress compared to POM are minimal. However, the average failure load for rubber is approximately 20% smaller compared to the average failure load for POM. Therefore it can be concluded that the test-results for POM are arguable and that rubber is the least promising material. Additional experiments with a new intermediary every test, might be able to prove this assumption.

The difference between the results of steel as an intermediary and the other materials is substantial: the characteristic initial crack stress is for steel twice as high as for aluminium and approximately 10 to 20 times as high as for nylon, rubber and POM.
3.4.1 Explanation of the results

To find an explanation for the test-results the test specimens are schematized with a ‘spring model’ (fig. 3.5). The total test specimen is schematized as a spring with a certain total spring-stiffness, which describes the relationship between the force on the spring and the elongation (or shortening).

With Hooke’s law and the basic formulas for stress and strain the ‘spring-stiffness’ for a test-specimen of an uniform material can be described:

\[ \sigma = E \cdot \varepsilon \]  \[1\]
\[ \sigma = \frac{F}{A} \]  \[2\]
\[ \varepsilon = \frac{\Delta L}{L} \]  \[3\]


\[ F = \frac{EA}{L} \cdot \Delta L \]
\[ \frac{EA}{L} = \text{‘spring – stiffness’} = C \]

For glass and every intermediary material the ‘spring-stiffness’ can now be calculated, depending on the Young’s modulus, the area and the length of the specimen (table 3.4).

Now the ‘spring-stiffness’ of the different materials is known, the axial deformation of the material can be calculated depending on the ratio of the ‘spring-stiffness’. If the intermediary material has a stiffness which is twice as low as the stiffness of the glass specimen, the axial deformation will be two times as high for the intermediary material compared to the axial deformation of the glass. The sum of the axial deformations of the intermediary and the glass is the total axial deformation which is registered during the experiments. The axial deformation of the materials of the test-specimens are summarized in table 3.4.

<table>
<thead>
<tr>
<th>Intermediary</th>
<th>Average initial crack load (m_{0,1}) [kN]</th>
<th>Standard deviation (s_{x,1}) [kN]</th>
<th>Characteristic initial crack load (F_{k,1}) [kN]</th>
<th>Characteristic initial crack stress (\sigma_{k,1}) [N/mm²]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>-2855,0</td>
<td>420,4</td>
<td>-2098,2</td>
<td>-209,8</td>
<td>100,0</td>
</tr>
<tr>
<td>Rubber</td>
<td>-756,3</td>
<td>356,4</td>
<td>-114,8</td>
<td>-11,5</td>
<td>5,5</td>
</tr>
<tr>
<td>POM-C</td>
<td>-907,7</td>
<td>444,9</td>
<td>-107,0</td>
<td>-10,7</td>
<td>5,1</td>
</tr>
<tr>
<td>Nylon</td>
<td>-989,2</td>
<td>388,4</td>
<td>-290,1</td>
<td>-29,0</td>
<td>13,8</td>
</tr>
<tr>
<td>Aluminium</td>
<td>-1514,6</td>
<td>249,9</td>
<td>-1064,9</td>
<td>-106,5</td>
<td>50,8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exp</th>
<th>Intermediary</th>
<th>‘Spring - stiffness’ (C) [N/mm]</th>
<th>Axial deformation (\Delta L_{\text{axial}}) [mm]</th>
<th>Transverse deformation (\Delta L_{\text{transverse}}) [mm]</th>
<th>Ratio (\Delta L_{\text{transverse}}) intermediary / glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Steel</td>
<td>1,75 E+07</td>
<td>-1,035</td>
<td>+0,259</td>
<td>0,5</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>5,83 E+07</td>
<td>-0,311</td>
<td>+0,518</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Rubber</td>
<td>2,50 E+04</td>
<td>-32,657</td>
<td>+40,822</td>
<td>1750,0</td>
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<tr>
<td></td>
<td>Glass</td>
<td>5,83 E+07</td>
<td>-0,041</td>
<td>+0,023</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>POM-C</td>
<td>2,60 E+06</td>
<td>-1,305</td>
<td>+4,566</td>
<td>47,1</td>
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<tr>
<td></td>
<td>Glass</td>
<td>5,83 E+07</td>
<td>-0,058</td>
<td>+0,097</td>
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</tr>
<tr>
<td>16</td>
<td>Nylon</td>
<td>3,00 E+06</td>
<td>-2,136</td>
<td>+8,331</td>
<td>45,5</td>
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<td></td>
<td>Glass</td>
<td>5,83 E+07</td>
<td>-0,110</td>
<td>+0,183</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Aluminium</td>
<td>6,90 E+07</td>
<td>-0,093</td>
<td>+0,307</td>
<td>1,7</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>5,83 E+07</td>
<td>-0,110</td>
<td>+0,184</td>
<td></td>
</tr>
</tbody>
</table>
Now the axial deformation of the materials is known, the axial strain ($\varepsilon$) can be calculated. The Poisson factor describes the relationship between the axial strain and transverse strain, so the transverse strain can also be defined. Subsequently the transverse deformation can be calculated for all the materials (table 3.4). When the transverse deformation becomes larger and larger, this model is not totally correct anymore. The force is introduced over a surface of 100 x 100 mm, and for instance for the case of rubber the elongation is 40mm which corresponds to a surface of 120 x 120 mm. But when the surface increases from 100 x 100 mm to 120 x 120 mm the forces are still only introduced over a surface of 100 x 100 mm, not the entire surface. The total increase in surface will be lower than calculated, because the calculations assume that the forces are introduced over the entire surface the entire time. This error becomes larger, when the transverse deformation becomes large.

With the ratio between the transverse deformation of the intermediary and the glass the test-results can be explained. If this ratio is below zero, this means that the transverse deformation of the glass is higher than the transverse deformation of the intermediary. This is only the case for steel as an intermediary. Due to friction-forces between the surface of the steel intermediary and the glass specimen, the steel prevents the glass from elongating in the transverse direction, thus introducing compression forces in the glass specimen (fig. 3.6). All other intermediary materials have a larger transverse deformation compared to the elongation of the glass, thus resulting in tension forces in the glass specimen (fig. 3.6 and fig. 3.1) and subsequently a low failure stress. The ratio between the transverse deformation of rubber and glass is the highest and would therefore result in the lowest failure stress. This corresponds with the initial expectations. The results, however, show that POM is the least promising material, but in the previous paragraph some reasons were given to doubt the test-results for POM.

In this paragraph the results are explained with a 2D-example, whereas in reality it will be a 3D-situation. The transverse deformations will be in two directions, rather than one. These deformations in different directions, partially counteract each other, which leads to combined deformations. This aspect will be discussed in more detail in the numerical research of chapter 7.
3.4.2 Crack analysis
All the figures of the crack-patterns are given in Appendix D. In figure 3.7 the characteristic crack-patterns of the glass panels with different intermediary materials are shown. Only one figure per intermediary material is shown, but the other crack-patterns were comparable to the shown figures.

The crack-pattern of the glass panel with steel as an intermediary immediately stands out from the rest. Only one small chip has been broken off from the glass panel, whereas the other intermediary materials show a lot more cracks dispersed over the entire surface of the glass panel. This phenomenon can also be explained by the horizontal compressive stresses in the glass panel by the steel intermediary. Cracks will occur when the ultimate tension-stress is reached. The glass panels with steel as an intermediary are horizontally (and vertically) compressed and therefore cracks cannot occur as easily: before the ultimate tension-strenght is reached the tension forces first have to overcome the compressive stress. This also explains why the first crack occurs at the edge or, to be more precise, at the corner: at this position the horizontal compressive stresses will be small.

The other intermediary materials show a crack-pattern which is quite dense, with cracks dispersed over the entire surface. The crack pattern of POM looks quite random, but for the crack patterns of rubber and nylon the cracks seem to emerge from one central point. The crack pattern of aluminium as an intermediary shows yet another trend: the cracks mostly concentrate a small distance from the edges. Why these different crack patterns occur exactly is difficult to explain with use of these experiments. The stresses in the glass panels should be analysed more carefully, which is the focus of the numerical research in chapter 7.

Furthermore it can be concluded that a larger initial crack load does not lead to a denser crack-pattern, not even when the crack patterns of the same intermediary material are compared.
3.4.3 Stress analysis

In paragraph 2.1.1 the visualization of stresses in glass with help of polarizer films was described. In figure 3.8 the stress patterns for an increasing external compressive load are shown for the different intermediaries.

In the top figures the external compressive load is zero, but at the edges the specimens light up as if there are stresses at these positions. However it is unlikely that stresses will be present in the glass, because float glass is used and the production technique of cutting and polishing will not lead to residual stresses in the glass. The fact that the edges do light up, probably has to do with the refraction of light off the edges. Additional measurements with a scattered light polariscope (SCALP-04, figure 3.9) confirm that there are no residual stresses in the edges. SCALP-04 sends a laser beam through the glass panel at an angle of about 45° (figure 3.10). Stress birefringence changes the polarisation of the laser beam. These changes are recorded by measuring the variation of the intensity of the scattered light along the laser beam with a camera. From this measurement data the stress profile through the panel thickness is determined. The minimum stress which can be registered is 4 MPa. From figure 3.11 it becomes clear that there are no residual stresses in the panels, neither in the center nor at the corners. [14]
The visualization with help of polarizer films is only qualitative: relative differences in stress at different positions can be visualized, but the amount of stress is unknown. It furthermore is not possible to distinguish compressive stresses from tensile stresses. Nevertheless some differences in the stress patterns are visible between the different intermediary materials. As the external load increases the darker the image gets. How the dark area ‘grows’ depends on the intermediary. For steel the dark area is present from the beginning over the full width of the glass specimen and grows in thickness from the vertical center of the panel. With nylon as an intermediary the dark area is present at the top and bottom of the glass specimen. The top part grows in thickness from the horizontal center until almost the entire surface is covered. The stress patterns of rubber and POM are similar to the pattern of nylon. With aluminium as an intermediary first the crack pattern emerges over the full height with a limited width and then increases in width.

This analysis shows that the stresses in the glass specimens with different intermediary material differ quite a lot. Because it is unknown whether these stresses are tensile or compressive stresses and how large the stresses are it is difficult to draw conclusions. A more extensive analysis with a Finite Element Model could provide some conclusions (chapter 7).
3.5 Conclusion

The goal of the experiments in this chapter is to determine which of the intermediary materials is the best suitable to introduce the forces into the glass panel, in such a way that stress concentrations and tension forces do not occur in the glass panels: this will result in a high load-bearing capacity of the column.

From these experiments it can be concluded that steel as an intermediary results in the highest characteristic initial crack stress. Statistical interpretation of five ‘identical’ experiments resulted in a characteristic initial crack stress of -209.8 N/mm² for steel which is twice as high as for aluminium and approximately 10 to 20 times as high as for nylon, rubber and POM.

Steel has a lower transverse elongation compared to the transverse elongation of glass, which results in horizontal compression forces in the glass due to friction between the surface of the steel intermediary and the glass specimen. Cracks occur when the tension-strength is reached and when horizontal (and vertical) compressive stresses are present in the glass panels the ultimate tension-strength is not reached as easily: the tension-forces first have to overcome the compressive forces.

The reason that steel has a lower transverse elongation is primarily because of its high Young’s modulus. A high Young’s modulus results in a small axial deformation and when the axial deformation is small, the transverse deformation will also be smaller. From this point of view the Young’s modulus of the intermediary material should be larger than the Young’s modulus of glass and the larger the Young’s modulus of the intermediary material, the larger the horizontal compressive forces (depending on the Poisson factor and coefficient of friction). A negative aspect of a high Young’s modulus is the fact that it cannot easily deform and adapt to the micro-profile of the glass. Irregularities in the surface of the glass specimen or the steel intermediary will result in stress-concentrations. The steel blocks used in these experiments were milled to a ‘totally’ flat surface, and from the test results it appears that the stress-concentrations were not a problem.

A remark should be made on the test-results and the occurrence of compressive forces in the glass panels with steel as an intermediary. When a glass column is made out of hundreds of layers of glass only the first (few) layer(s) at the bottom and the top are affected by the intermediary. When a steel intermediary is used horizontal compressive forces will only occur in the first few panels, so the panels in the center of the column are expected to fail at a lower overall stress. The specimens in the upcoming experiments are therefore expected to fail at a lower stress.
Chapter 4:
EXPERIMENTS B – INTERLAYER
4 EXPERIMENTS B – INTERLAYER

In paragraph 1.2 it became clear that an adhesive interlayer is a promising concept to stabilize the column. This, however, depends largely on the behaviour of the interlayer under compression. Because this behaviour is not a well-documented phenomenon experimental research is necessary to give insight in this behaviour.

4.1 Interlayer-specimens

The aim of the experiments is to analyze the effect of an interlayer on a stacked glass column and to investigate the behaviour of this interlayer. In order to do this the results of experiments with a stacked glass column without an interlayer should be compared to columns with different interlayers. For the interlayer basically two types of interlayer can be applied: adhesives or adhesive films.

ADHESIVES

Lots of different types of adhesives exist, but not all of them are suitable for glass. Types of adhesives which are often used for glass-glass connections are acrylates, cyanoacrylates and epoxies (table 4.1). Furthermore polyurethane and silicone-based adhesives are also used for glass. [15]

Acrylates are known to have good durability-properties and excellent optical properties. The mechanical properties of epoxies depend on its composition, formulation and curing and therefore a wide range of properties are possible. An important property of cyanoacrylates is that curing is activated by atmospheric moisture. For a glass column with a large surface for the adhesive the curing process would take up a long time, if it even cures totally. The edges of the surface of the adhesive will cure, because they are in contact with the surrounding air, but the glue in the center of

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Table 4.1 adhesives used to bond various materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Textiles</th>
<th>Composites</th>
<th>Glass &amp; Ceramics</th>
<th>Rubber</th>
<th>Plastics</th>
<th>Wood</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites</td>
<td>AC-PU-PVA</td>
<td>EP-IM-PE-PH</td>
<td>PU-PVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textiles</td>
<td>PVA-THM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: AC Acrylic/Acrylate EP Epoxy PU Polyurethane SI Silicone AA Anaerobic IM Imide PH Phenolic THM Thermoplastic hot melt CA Cyanoacrylate PE Polyester PVA Polyvinylacetate
the column will not. Therefore the glue in the center will not cure, or it would take a long time to cure. This property makes cyanoacrylates unsuitable for this application. Polyurethane adhesives are known to make tough, flexible bonds and should also be considered. Silicone-based adhesives could also be used but degradation over time is an unwanted effect of this type of adhesive. For the experiments the focus will lie on acrylates (AC), epoxies (EP) and polyurethane-adhesives (PU).

Even within these three categories of adhesives the properties differ quite a lot. In order to make a choice for the adhesives, different types of adhesives which were used in other graduation projects, dissertations, experimental studies, etc.[16, 17, 18, 19, 20, 21, 22, 23] and adhesives which were suggested by technicians of the most important adhesive manufacturers, were compared and analysed.

**ADHESIVE FILM**

An ‘adhesive’ film (AF) which is often used for glass is PVB-foil. Laminated glass is often made with this type of foil. However this production technique requires the foil to be applied under high pressure and high temperature in an autoclave, which becomes troublesome for large stacked structures with lots of layers of glass and PVB-foil. Adhesive strips or film which can be applied without use of an autoclave are preferable. For the sculpture of ‘Archangel Michael’ an adhesive transfer tape made by 3M has been used: 468MP (on an acrylate-basis) with a thickness of 0,13mm. For ‘the Glass Sphinx’ an adhesive film by the Acrylic Foam Tape Company (AFTC) has been used which is also on an acrylate-basis and has a thickness of 0,25mm.
COMPARISON ADHESIVE INTERLAYER

A list of demands for the properties of the adhesive interlayer is prepared and all the adhesives and adhesive films are rated for these properties. The demands for the properties can be arranged in seven different aspects.

1. Materials, size and shapes to be bonded:
2. Mechanical performances:
3. Physical and chemical performances:
4. Curing:
5. Aesthetics:
6. Production:
7. Economics:

The entire list of properties and demands is attached in Appendix E. In Appendix E the comparison of the different adhesives is shown and the choice of adhesives becomes clear in these tables.

Some properties are more important than other properties. An important property for the adhesive is the color: the adhesive should be transparent/colorless from an aesthetic point of view. Another important aspect is the method of curing. As discussed previously adhesives which cure by atmospheric moisture or by heat are undesirable. Furthermore the shrinkage and the Young’s modulus of the adhesive are important properties. To ensure that the two glass panes are connected evenly and homogeneously over the surface the shrinkage during curing should be minimized. Minor shrinkage will always occur and during appliance always minor irregularities (air bubbles etc.) will be present. This results in an inhomogeneous interlayer and then the Young’s modulus of the interlayer plays a role. If the interlayer has a high stiffness (i.e. high young’s modulus) the stresses cannot be redistributed over a larger surface. If the stiffness of the interlayer is low, the stresses can be redistributed and spread out evenly over the surface and therefore stress concentrations will be avoided, that is the expectation at least. In order to analyze whether or not this expectation is true different types of adhesives with different degrees Young’s moduli are used.

In table 4.2 some of these important properties, found in the technical datasheets delivered by the adhesive manufacturers, of the chosen adhesive interlayers are displayed. For polyurethane adhesives and the adhesive films some of the properties in the table below are unknown.

### Table 4.2 Choice of adhesives and adhesive films

<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
<th>Type</th>
<th>Young’s modulus [N/mm$^2$]</th>
<th>Method of curing</th>
<th>Shrinkage</th>
<th>Transparency</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photobond 4468</td>
<td>Delo</td>
<td>Acrylate (1C)</td>
<td>250</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+20</td>
</tr>
<tr>
<td>Photobond 4302</td>
<td>Delo</td>
<td>Acrylate (1C)</td>
<td>260</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+20</td>
</tr>
<tr>
<td>Akepox S010</td>
<td>Akemi</td>
<td>Epoxy (2C)</td>
<td>3000</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+16</td>
</tr>
<tr>
<td>Duopox AD821</td>
<td>Delo</td>
<td>Epoxy (2C)</td>
<td>114</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+8</td>
</tr>
<tr>
<td>Scotch-Weld DP610</td>
<td>3M</td>
<td>Polyurethane (2C)</td>
<td>800</td>
<td>+</td>
<td>?</td>
<td>++</td>
<td>+11</td>
</tr>
<tr>
<td>Adhesive film</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>468 MP</td>
<td>3M</td>
<td>Acrylic film</td>
<td>?</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>+25</td>
</tr>
<tr>
<td>Silvertape 8502</td>
<td>AFTC</td>
<td>Acrylic film</td>
<td>?</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>+25</td>
</tr>
</tbody>
</table>

1) In the datasheet the colour of the adhesive was stated as ‘very neutral’. In practice this means milky, which is undesirable.
A closer look into the comparison-table of Appendix E shows for the Acrylates that the Photobond GB368 has a higher total score than Photobond 4468. The only difference in this table is the costs: Photobond GB368 is cheaper, but this is because it can only be bought by a large amount (1 kilo compared to 50 grams for Photobond 4468). The price per kilo does not differ that much, and because only small amounts are necessary for this graduation project Photobond 4468 is chosen.

The main difference between the two chosen acrylates is that Photobond 4302 is an adhesive with ‘capillary action’, whereas Photobond 4468 has no ‘capillary action’. ‘Capillary action’ can be defined as the ascension of liquids through slim tube, cylinder or permeable substance due to adhesive and cohesive forces interacting between the liquid and the surface. This actually means that the adhesive can ‘suck’ itself into the voids between the glass panels due to capillary forces (fig. 4.1). The viscosity of Photobond 4302 is subsequently lower than the viscosity of Photobond 4468 (Appendix E). Excess glue, which is not sucked into the voids, does not cure, even under UV-lighting. This makes capillary UV-curing adhesives easier to clean. When large surfaces have to be covered with adhesive, it takes quite a lot of time before all the glue is sucked into the voids, which make it a time-consuming production process. Furthermore the shrinkage and Young’s modulus is about the same, but the elongation at tear for Photobond 4468 is higher.

For the epoxies the Akepox 5010 and Duopox AD821 are chosen because of the difference in Young’s modulus. As described previously this is an important aspect with respect to stress concentrations in the glass. For this reason an adhesive with a low and a high Young’s modulus are chosen with the highest scores in the comparison-table of Appendix E.

Research into polyurethane adhesives learned that this type of adhesive needs lots of chemical additives to become transparent. In general the quality (i.e. strength etc.) will be lower than for the epoxies and acrylate adhesives. One type of transparent polyurethane adhesives are used for the experiments: Scotch-Weld DP610.

For the adhesive films, 2 types are chosen which were used for Archangel Michael (Zwolle) and the glass Sphinx (Venlo). Both adhesive films are on an acrylic basis and the most important difference between the two tapes is the thickness (0,13 mm for 468MP and 0,25 mm for Silvertape 8502). Some properties of these adhesives, like the elongation at tear or the shrinkage, are unknown.
4.2 Application of the adhesive interlayer

The appearance, costs and the production process of a column with an adhesive interlayer depends largely on the application of the adhesive interlayer. Aspects which are important from this point of view are the surface over which the adhesive is applied and whether a liquid adhesive or an adhesive film is applied. These aspects are discussed in the following paragraphs.

4.2.1 Application over the surface

The interlayer can be applied in four different ways (fig. 4.2) ranging from application over a large surface to application over a small surface. The adhesive could be applied over the entire surface of the glass panels. A second option is to apply the adhesive over a small part of the surface. Thirdly the glass panes could be connected by applying the adhesive on a few spots. The last option is to make a dry stack of glass panels and to apply the adhesive afterwards on the edges. The surface over which the adhesive is applied is more important for a liquid adhesive than for an adhesive film. The surface over which the adhesive is applied can be compared from different points of view:

**Costs**

The (material-)costs are directly related to the amount of adhesive. The larger the amount of adhesive the more expensive the solution will be.

**Aesthetics**

Aesthetically the option with adhesive over the entire surface will be the most promising solution, providing that the adhesive can be applied without visual imperfections. When the adhesive is applied over a small surface or a few spots the front-line of the adhesive will always be visible and ingress of water and dirt is not avoided. Furthermore, the option with the glue on the edges will result in an unsatisfactory appearance, because this is the most visible part of the column.

**Load-bearing capacity**

As for the load-bearing capacity the options with an adhesive over a small surface and on a few spots are the least promising. Because the glue has a certain thickness, the glass panels are only connected to each other at these points, which results in stress concentrations. Whether the solution with adhesive over the entire surface or the solution with adhesive on the edges is the most promising, depends on the behaviour of the adhesive interlayer.

**Production process**

When the adhesive will be applied on the edges of the stacked panels, the adhesive can be applied over the entire column at once, resulting in a quick production process. When an adhesive is applied in-between the glass panels, this will be time-consuming. Especially when a large amount of glue is used, which needs to cure (depending on the curing-time). Because the adhesive films ‘cure’
Part 2 – The Stacked Column

Load-Bearing Glass Columns

Instantly, it does not have this disadvantage. A negative aspect of ‘instant curing’ is that the positioning of the glass panels is critical: the positioning has to be exactly right, because the position cannot be adjusted.

Safety

When the adhesive is applied over the entire surface, the interlayer can slow down crack-growth and prevent shards of glass from flying around. This results in a larger ‘post-initial crack strength’ and a safe failure-behaviour. When the adhesive is applied over a small surface, on a few spots or on the edges this is not possible, resulting in an unsafe failure behaviour.

Disassembly

Whether or not a column is easy to disassemble and recycle depends on how the glass panes are connected. When the panes are connected with an adhesive over a large surface it becomes harder to disconnect or disassemble the panes. From this point of view the option with an adhesive over the entire surface is undesirable. When the adhesive is applied on a few small spots, it is easy to disassemble the column for recycling.

Conclusion

The most promising solution appears to be the option with adhesive over the entire surface, because of safety issues and the aesthetic point of view. Whether or not this option also leads to a column with a high load-bearing capacity is unknown and will be investigated with experimental research. Unfortunately this solution is expensive, difficult to disassemble and the production process is time-consuming. However safety is the most important parameter and of all the solutions this solution appears to be the most promising one.

Remark

For an adhesive with capillary action the surface over which the adhesive is applied is not relevant. The adhesive should be applied on the edges and it ‘sucks’ itself into the voids between the two glass panels. The application can be seen as a combination of the application over the entire surface and at a few spots: the entire surface of the glass panels is covered by the adhesive, but only where there is a void between the two glass panes (fig. 4.3). Where the two glass panes are directly in contact with each other no adhesive is applied. So it appears that the adhesive is applied over the entire surface, but when you zoom in to the interlayer it actually is a micro-network of spots where the adhesive is applied (where the voids were) and the points of direct contact between the glass panels. What exactly happens when the capillary adhesive would be applied on a few spots on the first glass panel and afterwards the second panel is placed on top of it is quite unknown. Technicians of one of the adhesive manufacturers advised to apply the capillary adhesive on the edges so that method of application is used in this graduation project.
4.2.2 Application of a liquid adhesive vs. adhesive film

The previous paragraph focuses on the surface over which the adhesive is applied. This aspect is more important for a liquid adhesive than for an adhesive film. For an adhesive film it would be quite remarkable to cut the film, which comes in roles of different width, into pieces to apply the film over a small surface or just on a few spots. To apply the adhesive film on the edges is not advisable either, because this would result in an unsatisfactory appearance. Therefore application over the entire surface is the most desirable solution. How the application of an adhesive film compares to the application of a liquid adhesive is discussed below:

**Costs**

The (material-) costs of the liquid adhesives differs quite a lot, even within one type of adhesive. Furthermore the amount of adhesive which is necessary depends on the optimum thickness, which also varies quite a lot (i.e. for the adhesives used in the experiments between 0.20 and 2.00 mm).

This makes it difficult to compare the costs with the costs of adhesive films. In general the costs of adhesive films are lower, especially when the production costs are also taken into account. The production process for a liquid adhesive is more difficult and time consuming (see ‘production process’ below) and therefore the production costs will be higher for the liquid adhesives.

**Aesthetics**

The adhesive films are not entirely transparent and it is difficult to apply the adhesive without visual imperfections like air bubbles. Figure 4.4 shows the application of an adhesive film for the Glass Sphinx in Venlo. In this figure it becomes clear that the film is translucent and a lot of imperfections are visible. For a liquid adhesive it is easier to apply the interlayer without air bubbles, because the adhesive is liquid and if applied correctly the air can flow out. Air bubbles could be eliminated altogether if a vacuum is applied during adhesive curing. Furthermore it is questionable whether visual imperfections like air bubbles are visible or not when the panels are stacked. One looks primarily at the end faces of the panels, so visual imperfections in between the glass panels might even be unnoticeable.

**Load-bearing capacity**

The behaviour and the load-bearing capacity of an adhesive interlayer under compressive loads is unknown. Therefore it is difficult to predict whether or not an adhesive film will be better or worse than a liquid adhesive from a structural viewpoint. A liquid adhesive can adapt to the micro-profile of the glass panels and because of that stress-concentrations are avoided. An adhesive film has a certain thickness over the entire surface and cannot (as easily) adapt to the micro-profile of the glass panels. This could be an aspect to expect that a liquid adhesive will be more promising, depending on the type and properties of the adhesives of course.

**Production process**

The production process of a column with a liquid adhesive is more complicated than the production process with an adhesive film. In the case of a liquid adhesive it is difficult to estimate how much glue is necessary, especially when non orthogonal shapes are used. When too small an amount of adhesive is used this results in an inhomogeneous connection which is undesirable. Therefore always a surplus of adhesive should be applied. Subsequently the adhesive spills over the edges and needs to be cleaned afterwards. Secondly the thickness of the adhesive interlayer is another important aspect. Different spacers can be used to ensure that the thickness of the adhesive interlayer is
uniformly applied and is comparable to the optimum thickness for the given adhesive. The different options are discussed in paragraph 4.2.3. Thirdly a liquid adhesive needs time to cure and therefore results in a time-consuming production process. An adhesive film does not have these disadvantages. There is no need to estimate the amount of glue. The shape of film can be cut exactly to the shape of the glass panel (even after application) so there is no need for cleaning. Furthermore because it is a linear product it has a certain thickness so no spacers are necessary. The adhesive film cures instantly, which results in a quick production process. However, a negative aspect of ‘instant curing’ is that the positioning of the glass panels is critical: the positioning has to be exactly right, because the position cannot be adjusted.

Safety
Both the adhesive films and liquid adhesives can slow down crack growth and prevent shards of glass from flying around depending on the shear strength of the adhesive. In general no substantial difference exists between the shear strength of a liquid adhesive and the shear strength of an adhesive film. This property varies quite a lot for both the liquid adhesives as the adhesive films. Therefore from a safety point of view, in general, no differences exist between the safety of a column with an adhesive film as interlayer or a liquid adhesive.

Disassembly
The ease of which the column is disassembled depends on the strength of the interlayer. Again, the strength of the adhesive films/liquid adhesives varies quite a lot and therefor, in general, no substantial difference can be defined for the disassembly of columns with both types of interlayer.

Conclusion
From the production process-criteria and the costs, the option with an adhesive film is more desirable. However, adhesive films are never totally transparent and have a lot of visual imperfections, so from an aesthetics point of view the option with a liquid adhesive is more desirable. The load-bearing capacity of both options is unknown, but the expectation is that the liquid adhesive can reduce stress concentrations, because it can adapt to the micro-profile of the glass panels. The experiments should provide information on this subject.
4.2.3 Points of attention for the liquid adhesive

Some additional aspects with respect to the application of the liquid adhesive over the entire surface play a role. These aspects predominantly play a role for the liquid adhesives, not for the adhesive films. First of all, how to apply the adhesive with the least amount of visual imperfections such as air bubbles is an important aspect. Furthermore it is important to make sure that the thickness of the adhesive interlayer is uniformly applied and is comparable to the optimum thickness for the given adhesive. This results in glass panels which are connected parallel to each other.

The adhesive can be applied in three different ways (fig. 4.5):

First of all a dot of glue can be applied in the middle of the panels and when the second panel is placed on top of the other panel covered with glue, the adhesive will spread out. Air can flow away, making sure no air-bubbles are trapped within the adhesive.

A second option is to apply the adhesive in a cross in the center of the panel. In this way the air can still flow out, but to cover the entire surface a smaller amount of adhesive is necessary. When the adhesive is applied in a cross: the corners are covered as well, whereas for the dot of glue the adhesive will spill over the side-edges before the corners are covered.

A third option is to spread out the glue with a notched spreader, making sure the entire surface is covered before the second glass panel is placed. For this option it is easier to apply the right amount of glue, but air bubbles will be trapped within the adhesive because the air cannot flow away.

Two basic methods are tested to ensure that the thickness of the interlayer is comparable to the optimum thickness and is approximately the same over the entire surface.

To ensure a certain bond line-thickness glass beads are sometimes added to the adhesive as a spreader (fig. 4.6). The thickness of these glass beads ranges from 20 μm to 40 mm and the deviations in thickness and roundness are very small. The optimum thickness for the chosen adhesives are 0,20 mm, 0,25 mm or 2,00 mm. Due to the small deviation in the thickness of the glass beads, the optimum thickness can be achieved with a very high precision. A negative aspect is the strength and stiffness of the glass beads, which is higher than the strength and stiffness of the adhesive itself. When the test-specimens are compressed the stresses will concentrate around these glass beads rather than around the adhesive. Stress concentrations in glass should be avoided by any means, so this is a negative aspect of the application of glass beads.

A second option is to use fishing wire as a spacer. The strength and stiffness of nylon is lower than for glass, which would not result in stress concentrations. Furthermore the deviations in thickness are small, so the optimum thickness can be achieved with a high precision.
All these options were tested with a few small scale experiments. So for every method of application of glue (i.e. dot, cross and spread out) the different spacer-solutions (i.e. no spacer, glass beads, fishing wire) were tested. In figure 4.5. the three application-methods with glass beads as spacers are visible. The glass beads are hardly visible in this figure.

From the different application-methods the application of the glue in a cross proves to be most promising solution. When the adhesive is applied as a dot, the glue spills out over the edges before the corners are covered. Subsequently a lot of excess glue is necessary to cover the entire surface, which is not cost-effective and leads to quite a messy production process. When the glue is spread out with a notched spreader a lot of air-bubbles are trapped, which leads to visible imperfections. When the adhesive is applied in a cross the visible imperfections are limited to zero almost and the amount of adhesive which is necessary to cover the entire surface is far less compared to the application in a dot. For these small-scale experiments with squared glass specimens the application in a cross is the most suitable. When the adhesive needs to be applied over large glass specimens with non-orthogonal shapes it is difficult to apply the glue in a crossed shape and to estimate the amount of glue which is necessary. It then becomes more promising to spread out the adhesive. Visual imperfections in the form of air bubbles could be avoided to apply the adhesive under vacuum, but this falls beyond the scope of this graduation project.

From the different spacer options, fishing wire as a spacer proves to be the most promising: the strength and stiffness of glass beads are too high, which results in stress concentrations. Furthermore the glass beads are clearly visible in the adhesive interlayer, which results in visual imperfections. Measurements on the adhesive interlayer thickness prove that without a spacer the thickness of the adhesive interlayer is not the same over the entire surface. Therefor the glass panels are not parallel to each other. Fishing wire as a spacer is hardly visible and results in approximately the same thickness over the entire surface which can be compared to the optimum thickness.

For the test-specimens in the upcoming series of experiments the glue is applied in a cross with fishing wire as a spacer (fig 4.7). For one epoxy-glue the optimum thickness is 2,0 mm. Fishing wire of such a thickness was not available, so aluminium strips were used as a spacer. These strips were placed in the corners temporarily until the glue cured to the handling strength. Afterwards they were removed, leaving small gaps at the corners where the aluminium strips used to be positioned.
4.3 Test setup
In this series of experiments different adhesive interlayers are analysed. Two glass panels were connected with five different adhesives and two adhesive films (fig. 6.8). The results of the experiments are compared to a dry stack of two glass panels.

The float-glass panels have dimensions of 100 x 100 x 12 mm with ground and polished edges. For the adhesives the optimum bond line thickness is used depending on the adhesive (i.e. 0.20 mm, 0.25 mm or 2.00 mm). The adhesive films have thicknesses of 0.13 mm and 0.25 mm. Steel blocks are used as an intermediary for all the experiments.

For every type of interlayer, five ‘identical’ experiments have been conducted to achieve a certain amount of reliability. The experiments are stopped when multiple cracks have occurred or in some occasions when total failure had occurred. The end of the life-cycle of a glass column is reached when the structure entirely collapses. Another important moment in the life-cycle of a glass column is the moment the initial crack occurs. In the previous series of experiments the experiments were stopped when an initial crack occurred. In the new series of experiments the initial crack occurred more or less at the same moment for most of the adhesive interlayers, because of an irregularity in the steel intermediary. A more detailed description of the crack-analysis is provided in paragraph 4.5.3. In order to analyze the effect of different adhesive interlayers the experiments are not stopped at this moment but only after multiple cracks have occurred. For these experiments ‘multiple cracks’ are defined as cracks at different locations, or cracks of a larger scale which occur abruptly at the same position as the previous crack.

The goal of this series of experiments is to determine which of the adhesive interlayer is best suitable to connect the glass panels to each other, which will result in a high load-bearing capacity of the column.
4.4 Expectations

The behaviour of an adhesive interlayer under compression is quite unknown. Therefore it is difficult to predict whether or not the adhesive interlayer plays a positive or negative role in the load-bearing capacity of the column. The interlayer could be able to redistribute the forces, so stress concentrations are avoided and an interlayer might be able to slow down crack growth. These aspects lead to a positive effect on the load-bearing capacity of the column. However the flow of the interlayer is an important (negative) aspect in the deformations and the load-bearing capacity of the column.

It is difficult to predict whether an adhesive film will be better or worse than a (liquid) adhesive from a structural viewpoint. A (liquid) adhesive can adapt to the micro-profile of the glass panels and because of that stress-concentrations are avoided. An adhesive film has a certain thickness over the entire surface and cannot (as easily) adapt to the micro-profile of the glass panels. This might be an aspect to expect that a liquid adhesive is more promising, depending on the type and properties of the adhesives of course. In general acrylates are supposed to be of the highest quality, then the epoxies and then the polyurethanes. So from this point of view acrylates are supposed to be the most promising type of adhesive and polyurethanes the worst, but this depends on the specific properties.

One of these properties is the Young’s modulus of the adhesive: a ‘flexible’ adhesive (i.e. low Young’s) might be able to redistribute the forces, so a flexible adhesive appears to be the most suitable. A negative effect of the ‘flexible’ adhesives is the fact that the axial deformations will be larger.

The axial deformations are expected to be the smallest for the specimen without any interlayer, as the stiffness of the interlayer is in general lower than the stiffness of the glass panels. Another important aspect, regarding the axial deformations, is the capillary action of the adhesive. An adhesive with capillary action is applied only in the voids between two glass panels, so the deformation of the interlayer will be limited to a minimum. The glass however is in direct contact with each other, which could play a negative role, because stress concentrations will occur. From this point of view an adhesive without capillary action would be most promising, but then the total axial deformations will be larger. The total axial deformations should not be too large: when the axial deformations become too large the top point of the columns lowers too much to be able to act as a bearing for the structural elements which are connected to the column. The axial deformation is expected to be the lowest for an adhesive with capillary action. Furthermore the thicker the adhesive interlayer, the larger the deformations (depending on the stiffness). Therefore an interlayer with a smaller thickness is expected to be desirable.
4.5 Results

4.5.1 Initial crack
As described in paragraph 4.3 the experiments were stopped when multiple cracks had occurred. For these experiments ‘multiple cracks’ are defined as cracks at different locations, or cracks of a larger scale which occur abrupt at the same position as the previous crack. The first three cracks are analysed for the different intermediary materials (appendix F, figure 4.9 and table 4.3 - 4.5).

First of all it became clear that the influence of the steel intermediary material on the moment the initial crack occurred was high compared to the influence of the adhesive interlayer. The initial crack occurred for multiple specimens with different interlayers at exactly the same position relative to the steel blocks. When the positions of the steel blocks were changed (top block at the bottom and vice versa), the position of the first crack also changed to exactly the same position relative to the steel blocks. Furthermore the average initial crack load was for most of the materials the same (around 920-960 kN), although the properties of the adhesive interlayers differ substantially. Furthermore the standard deviation is large for the different experiments. These aspects make it quite hard to reach definitive conclusions about these interlayers, but they do give insight in the behaviour of the interlayers.
The first question one can ask is whether the interlayer has a positive or negative influence in the load-bearing capacity of the column. From the test results it appears that an adhesive interlayer is beneficial, depending on the type of adhesive and its properties.

The characteristic initial crack stress was for three adhesives (i.e. both the acrylates (P4468/P4302) and one epoxy (AD821)) higher than the characteristic initial crack stress of the specimens without an interlayer. Four adhesive interlayers showed a lower characteristic initial crack stress. A remark needs to be made: the epoxy AD821 showed a substantially higher average initial load, but in one experiment the initial crack occurred at a low stress. Therefore the standard deviation is very large and subsequently the characteristic initial crack stress is small. Therefore this specific test-result is arguable and thus it was rejected. A new test-specimen was prepared and the experiment was repeated for this specific specimen. In this experiment the initial crack load was more comparable to the other test-results, resulting in a substantially higher characteristic initial crack stress.

For the second crack and the third crack the same trend is visible. For the second crack only one acrylate (P4302) and one epoxy (AD821) reach a higher characteristic stress. For the third crack again both acrylates and the epoxy AD821 have a higher crack stress.

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Average initial crack load (m_{k,1}) [kN]</th>
<th>Standard deviation (s_{k,1}) [kN]</th>
<th>Characteristic initial crack load (F_{k,1}) [kN]</th>
<th>Characteristic initial crack stress (\sigma_{k,1}) [N/mm(^2)]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interlayer</td>
<td>-952,0</td>
<td>189,2</td>
<td>-611,4</td>
<td>-61,1</td>
<td>73,6</td>
</tr>
<tr>
<td>P4468 (AC)</td>
<td>-923,5</td>
<td>94,4</td>
<td>-753,5</td>
<td>-75,4</td>
<td>90,8</td>
</tr>
<tr>
<td>P4302 (AC)</td>
<td>-938,2</td>
<td>150,1</td>
<td>-668,0</td>
<td>-66,8</td>
<td>80,5</td>
</tr>
<tr>
<td>A5010 (EP)</td>
<td>-948,3</td>
<td>226,0</td>
<td>-541,6</td>
<td>-54,2</td>
<td>65,3</td>
</tr>
<tr>
<td>AD821 (EP)</td>
<td>-1966,9</td>
<td>631,8</td>
<td>-829,6</td>
<td>-83,0</td>
<td>100,0</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>-958,6</td>
<td>449,8</td>
<td>-149,0</td>
<td>-14,9</td>
<td>18,0</td>
</tr>
<tr>
<td>468MP (AF)</td>
<td>-543,0</td>
<td>374,2</td>
<td>-10,0</td>
<td>-10,0</td>
<td>0,0</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>-275,4</td>
<td>304,0</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Average 2nd crack load (m_{k,2}) [kN]</th>
<th>Standard deviation (s_{k,2}) [kN]</th>
<th>Characteristic 2nd crack load (F_{k,2}) [kN]</th>
<th>Characteristic 2nd crack stress (\sigma_{k,2}) [N/mm(^2)]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interlayer</td>
<td>-1701,0</td>
<td>188,3</td>
<td>-1362,1</td>
<td>-136,2</td>
<td>93,0</td>
</tr>
<tr>
<td>P4468 (AC)</td>
<td>-1757,7</td>
<td>411,9</td>
<td>-1016,3</td>
<td>-101,6</td>
<td>69,4</td>
</tr>
<tr>
<td>P4302 (AC)</td>
<td>-1960,2</td>
<td>275,4</td>
<td>-1464,5</td>
<td>-146,5</td>
<td>100,0</td>
</tr>
<tr>
<td>A5010 (EP)</td>
<td>-1324,2</td>
<td>241,6</td>
<td>-889,3</td>
<td>-88,9</td>
<td>60,7</td>
</tr>
<tr>
<td>AD821 (EP)</td>
<td>-2272,4</td>
<td>474,3</td>
<td>-1418,6</td>
<td>-141,9</td>
<td>96,9</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>-1443,0</td>
<td>312,2</td>
<td>-881,0</td>
<td>-88,1</td>
<td>60,1</td>
</tr>
<tr>
<td>468MP (AF)</td>
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<td>416,4</td>
<td>-64,0</td>
<td>-6,4</td>
<td>4,4</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>-467,0</td>
<td>484,7</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Average 3rd crack load (m_{k,3}) [kN]</th>
<th>Standard deviation (s_{k,3}) [kN]</th>
<th>Characteristic 3rd crack load (F_{k,3}) [kN]</th>
<th>Characteristic 3rd crack stress (\sigma_{k,3}) [N/mm(^2)]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interlayer</td>
<td>-2472,4</td>
<td>490,9</td>
<td>-1544,5</td>
<td>-154,5</td>
<td>84,2</td>
</tr>
<tr>
<td>P4468 (AC)</td>
<td>-2501,1</td>
<td>413,1</td>
<td>-1757,5</td>
<td>-175,8</td>
<td>95,9</td>
</tr>
<tr>
<td>P4302 (AC)</td>
<td>-2356,4</td>
<td>305,9</td>
<td>-1805,7</td>
<td>-180,6</td>
<td>98,5</td>
</tr>
<tr>
<td>A5010 (EP)</td>
<td>-1793,0</td>
<td>252,0</td>
<td>-1339,3</td>
<td>-133,9</td>
<td>73,0</td>
</tr>
<tr>
<td>AD821 (EP)</td>
<td>-2543,9</td>
<td>394,2</td>
<td>-1834,4</td>
<td>-183,4</td>
<td>100,0</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>-2146,0</td>
<td>542,4</td>
<td>-1169,7</td>
<td>-117,0</td>
<td>63,8</td>
</tr>
<tr>
<td>468MP (AF)</td>
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<td>335,3</td>
<td>-651,7</td>
<td>-65,2</td>
<td>35,6</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>-1641,5</td>
<td>624,9</td>
<td>-516,6</td>
<td>-51,7</td>
<td>28,2</td>
</tr>
</tbody>
</table>
The second expectation was that a liquid adhesive would be more promising than an adhesive film. Two adhesive films are used in these series of experiments and both these films appeared to have the lowest characteristic crack stress for the first crack, the second crack and the third crack as well. Furthermore the difference between these adhesive films and the other liquid adhesives is quite substantial. From this it can be concluded that these types of adhesive films are less suitable for this application than all the other liquid adhesives which were used for these experiments: a liquid adhesive can adapt to the micro-profile of the glass panels, whereas an adhesive film (with the same thickness over the entire surface) is not able to do this. Because of these results it appears that adhesive films are less suitable than liquid adhesives.

From the different types of liquid adhesives the acrylates were expected to be the most promising adhesive-type. The experiments confirm this partially. In all the cases both the acrylates (P4468 and P4302) showed a higher characteristic crack stress compared to the stress of polyurethane adhesives and one epoxy (A5010). The other epoxy-adhesive (AD821) however, shows for the initial crack and the third crack a higher characteristic stress than both the acrylates.

This can be explained when the properties of the adhesives are compared. The adhesives with low Young’s moduli (i.e. both the acrylates and epoxy AD821) prove to be the best. The other epoxy (A5010) and the polyurethane adhesive (DP610) have a higher Young’s modulus, which results in a lower characteristic initial crack stress. From this it can be concluded that an adhesive with a low Young’s modulus is desirable. Furthermore it can be concluded that the influence of the Young’s modulus on the characteristic initial crack stress is higher than the influence of the adhesive type.
4.5.2 Axial deformation

Another aspect for a glass column is the total axial deformation, because the column exists of layers of different materials with different stiffness’s.

Table 4.6 shows the initial axial deformations at a stress from 1 to 50 N/mm$^2$. The value of 1 N/mm$^2$ is because of the settings of the CTM and at stresses higher than 50 N/mm$^2$ the relationship between the load and deformation is linear. The initial deformations are analysed because they element are expected to be relatively large for a layered element like a stacked column. These initial axial deformations could lead to problems during assembly of the column. When a stacked column is assembled and other building components are connected to the column, it might be the case that the initial axial deformations are so large that the column isn’t able to serve as a bearing for the other building components anymore, because the other building components (like beams or floors) cannot be assembled perfectly horizontal.

Table 4.7 shows the additional deformation at a stress from 50 to 170 N/mm$^2$. The force-displacement relationship is linear over this trajectory and the value of 170 N/mm$^2$ is chosen so that all specimens reach this stress.

The deformations are registered by the internal measurement equipment of the CTM, which are not really accurate. So for definitive conclusions the deformations should be measured with more accurate measurement devices. Nevertheless this analysis can provide some insight in the axial deformations.

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Type</th>
<th>Thickness [mm]</th>
<th>Young’s modulus [N/mm$^2$]</th>
<th>Mean initial axial deformation $m_{axial,ini}$ [mm]</th>
<th>Standard deviation $s_{axial,ini}$ [mm]</th>
<th>Characteristic initial axial deformation $ΔL_{axial,ini}$ [mm]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interlayer</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.31</td>
<td>0.02</td>
<td>-0.35</td>
<td>106.1</td>
</tr>
<tr>
<td>P4468 (AC)</td>
<td>0.20</td>
<td>250</td>
<td>-</td>
<td>0.32</td>
<td>0.03</td>
<td>-0.36</td>
<td>109.1</td>
</tr>
<tr>
<td>P4302 (AC)</td>
<td>0.00</td>
<td>260</td>
<td>-</td>
<td>0.34</td>
<td>0.01</td>
<td>-0.36</td>
<td>109.1</td>
</tr>
<tr>
<td>A5010 (EP)</td>
<td>2.00</td>
<td>3000</td>
<td>-</td>
<td>0.42</td>
<td>0.07</td>
<td>-0.54</td>
<td>163.6</td>
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<tr>
<td>AD821 (EP)</td>
<td>0.20</td>
<td>114</td>
<td>-</td>
<td>0.37</td>
<td>0.03</td>
<td>-0.43</td>
<td>130.3</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>0.25</td>
<td>600</td>
<td>-</td>
<td>0.32</td>
<td>0.01</td>
<td>-0.33</td>
<td>100.0</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>0.40</td>
<td>0.05</td>
<td>-0.52</td>
<td>157.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Type</th>
<th>Thickness [mm]</th>
<th>Young’s modulus [N/mm$^2$]</th>
<th>Mean additional axial deformation $m_{axial,add}$ [mm]</th>
<th>Standard deviation $s_{axial,add}$ [mm]</th>
<th>Characteristic additional axial deformation $ΔL_{axial,add}$ [mm]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interlayer</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-0.51</td>
<td>0.01</td>
<td>-0.53</td>
<td>100.0</td>
</tr>
<tr>
<td>P4468 (AC)</td>
<td>0.20</td>
<td>250</td>
<td>-</td>
<td>-0.53</td>
<td>0.03</td>
<td>-0.58</td>
<td>109.4</td>
</tr>
<tr>
<td>P4302 (AC)</td>
<td>-</td>
<td>260</td>
<td>-</td>
<td>-0.46</td>
<td>0.12</td>
<td>-0.68</td>
<td>128.3</td>
</tr>
<tr>
<td>A5010 (EP)</td>
<td>2.00</td>
<td>3000</td>
<td>-</td>
<td>-0.58</td>
<td>0.05</td>
<td>-0.67</td>
<td>126.4</td>
</tr>
<tr>
<td>AD821 (EP)</td>
<td>0.20</td>
<td>114</td>
<td>-</td>
<td>-0.54</td>
<td>0.03</td>
<td>-0.59</td>
<td>111.3</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>0.25</td>
<td>800</td>
<td>-</td>
<td>-0.53</td>
<td>0.01</td>
<td>-0.54</td>
<td>101.9</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>-0.57</td>
<td>0.01</td>
<td>-0.59</td>
<td>111.3</td>
</tr>
</tbody>
</table>
The expectation was that the axial deformations (both initial and additional) for the specimen without any interlayer would be the smallest. The results verify the expectations regarding the additional deformations, but for the initial deformations the polyurethane adhesive are smaller (although the difference is only 6.1%). The fact that the results show that the polyurethane adhesive has the lowest characteristic initial deformations can be explained by its properties: the optimum interlayer thickness is relatively small in combination with a relatively high Young’s modulus.

The influence of these properties becomes even clearer when the largest characteristic axial deformations are analysed: both the initial and additional deformations are the largest for the specimen with epoxy adhesive A5010 as an interlayer. Surprisingly, this is the adhesive with the highest Young’s modulus so, the axial deformations were not expected to be the largest for this type of adhesive. However, the interlayer thickness is eight to fifteen times larger than the other thickness which explains the results. From this it can be concluded that the interlayer thickness plays a more important role than the Young’s modulus of the interlayer. The results for the adhesive films seem to verify this conclusion. The adhesive film with an interlayer thickness which is twice as high results in substantially larger axial deformations. However, the Young’s moduli of these adhesive films are unknown which makes it difficult to compare the results.

The specimens with the capillary adhesive (P4302) was expected to have relatively low axial deformations, which are comparable to the axial deformations of the specimens without an interlayer. The characteristic initial axial deformations for the specimens with the capillary adhesive are larger by only a few percent. The characteristic additional deformations, however, are substantially larger for the specimen with the capillary adhesive (28.3 percent larger). This leads to believe that the interlayer thickness of an adhesive is not really 0. A small interlayer thickness would explain that the axial deformations are larger for the specimens with the capillary adhesive.

The results show that the initial axial deformations are relatively large, compared to the additional axial deformations. It, however, is difficult to predict what the influence is of these initial axial deformations on the assembly of the stacked column and adjoining building components in practice. This depends on the dead-loads of the adjoining building components and the length of the column etc.
### Ultimate failure

The majority of the experiments were stopped when an initial crack had occurred. In three cases (unintentionally) ultimate failure had also occurred. Figure 4.10 shows what was left of these three glass panels with the adhesive interlayer in-between. The test-specimens virtually explode and the only thing that was left of the specimens was glass crumbs. Even the steel intermediary blocks of steel grade S355 were damaged, which shows how high the stresses were. New steel intermediary blocks had to be made and milled so that the surfaces are totally flat again.

When total failure occurred no indication could be noticed in the force-displacement diagrams, so it was difficult to predict when total failure was about to occur. Because the forces were so high, which led to unsafe situations during the experiments, and because for every experiment new steel intermediary blocks were necessary, the experiments were stopped before total failure had occurred.

However, for the specimens with the adhesive films as interlayer, it was possible to notice when ultimate failure was about to occur. In figure 4.9 it can be noticed that the deformations begin to increase more rapidly at the end. So for these specimens the experiments were only stopped until a change in the force-displacement diagrams was visible. A characteristic ultimate failure stress can be calculated: 340,4 (468MP) and 356,7 N/mm² (ST8502) (table 4.8). At this stress the specimens did not fail yet, but were about to fail. Therefore the actual failure stress will be even higher, although the difference would be minimal. The failure stress is comparable to the crushing strength of glass as found in the literature: 325 N/mm² [3]. From this it can be concluded that the specimens with the adhesive film as an interlayer have a large additional capacity to withstand loads after the first crack has occurred. This also holds true for the liquid adhesives. In some cases, unintentionally, ultimate failure had occurred for some liquid adhesives. One specimen with Akepox5010 as an adhesive interlayer failed at a stress of 334,2 N/mm², whereas the first crack occurred at 91,2 N/mm². Two specimens with AD821 as an interlayer failed respectively at a stress of 267,6 and 324,3 N/mm², whereas the initial cracks occurred at 152,3 and 300,8 N/mm². Furthermore the specimen, for which ultimate failure did not occur, had been subjected to substantially higher stresses than the initial crack stress and still ultimate failure did not occur. From this it can be concluded that all the specimens with different adhesive interlayers have a large additional capacity to withstand loads after the first crack has occurred, although differences in the additional capacity are noticeable.

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>468MP (AF)</th>
<th>ST8502 (AF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ultimate failure load</td>
<td>- 3551,2</td>
<td>- 3650,4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>81,6</td>
<td>46,5</td>
</tr>
<tr>
<td>Characteristic ultimate failure load</td>
<td>- 3404,4</td>
<td>- 3566,8</td>
</tr>
<tr>
<td>Characteristic ultimate failure stress</td>
<td>- 340,4</td>
<td>- 356,7</td>
</tr>
<tr>
<td>Percentage [%]</td>
<td>95,4</td>
<td>100,0</td>
</tr>
</tbody>
</table>
When no cracks are accepted, it would not be possible to design a column with the adhesive film, because the characteristic initial crack stress is zero. However the initial crack does not lead to ultimate failure of the specimen: only at a stress well over 300 N/mm² the specimen will fail. This however means that cracks in the glass of the column should be accepted. The crack-pattern just before ultimate failure is visible in figure 4.11. Cracks in this extent will never be accepted, but maybe a small amount of cracks can be accepted: a closer look at Archangel Michael shows that cracks have occurred in this sculpture as well (fig. 4.12). These cracks are accepted, because it still stands in the center of the market-square in Zwolle without any complaints or doubts on the structural integrity. In the case of the glass Sphinx in Venlo the engineers also accept small cracks to occur [Error! Bookmark not defined.].

Whether or not cracks need to be accepted from an aesthetic point of view, and to what extent, is a question which falls beyond the scope of this graduation project. From a structural point of view some initial cracks could be accepted when an initial crack does not lead to ultimate failure of the column and a safe failure behaviour can still be guaranteed.
4.5.4 Crack analysis

In these experiments it became clear that the influence of the steel intermediary material on the moment the initial crack occurred was relatively high. The initial crack occurred for multiple specimens with different interlayers at exactly the same position relative to the steel blocks. Furthermore the crack started at the surface where the glass is in contact with the steel intermediary and grew to the middle of a single glass panel (fig. 4.13). So the single glass panel was not cracked over the full height, but only over half its height. This can be explained by the presence of horizontal compression forces due to the steel intermediary blocks.

Although special care has been taken to assure that the steel blocks are as flat as possible (by the use of a milling machine), the appearance of a crack like this, leads to believe that there is some kind of imperfection in the flatness of the steel block. If there is a small protruding bump at that position this will lead to splitting forces at the edge of the glass panel. This would explain that for specimens with different interlayers the crack occurs at exactly the same position. Furthermore this explains that the crack grows from the surface of the glass panel, which is in contact with the steel block to the middle of the glass panel.

Another aspect about the cracks became visible when the experiments were stopped. When the experiments were stopped, the external compression load disappears quickly and therefore the horizontal compressive loads in the glass specimen, due to the steel intermediary blocks, disappears also. This becomes visible in the crack pattern, because at the moment the experiments were stopped, the cracks grew immediately over the entire surface.
4.5.5 Stress analysis

The figures of the stresses of the two acrylate adhesives are quite similar to the figure of the stresses without an interlayer (fig. 4.14). When these figures are compared to the stress-figures with different intermediary materials (paragraph 3.4.3) these figures are more comparable to the figures with aluminium as an intermediary, even though steel is used as an intermediary. From this it can be concluded that the adhesive interlayer clearly has an important influence on the stresses in the glass panels.

The epoxy adhesives show yet another stress distribution, especially adhesive interlayer A5010. Epoxy AD821 shows a comparable stress distribution as the acrylates and the specimen without interlayer, although the dark part for epoxy AD821 grows from one edge and for the other specimens the dark part grew from somewhere in the horizontal center of the specimens to the edges.

Polyurethane adhesive DP610 and the adhesive film 468MP show a stress distribution which is quite similar to the stress distribution of the single glass panel with steel as an intermediary. The other adhesive film (ST8502) shows an entirely different stress distribution. For this adhesive film the initial crack occurred at a low stress load of 14,3 N/mm² and therefore all these figures are comparable to the second figure of the other specimens.

From this analysis it can be concluded that the interlayer does have an important influence on the stresses in the glass panel. Because of the qualitative nature of this analysis method, it is not entirely clear whether the stresses are compression stresses or tension stresses. Furthermore the amount of stress cannot be determined with this method either. Fact is that the interlayer does have an influence on the stresses, but numerical research or another analysis method should be used to provide more information on this subject. This however falls beyond the scope of this research project.

In the top figures no external compression load is subjected to the glass panels. The edges of the panels do light up, as if stresses are present at these positions. Additional measurements with a scattered light polariscope (SCALP-04) confirmed that there are no residual stresses in the edges (paragraph 3.4.3). For the specimens with the two epoxies as an interlayer not only the edges light up, but so does the center of the specimens. Again additional measurements with the SCALP-04 measurement device confirm that no residual stresses are present in the center (and at the edges) of the panels. Why the specimens light up when the stresses are analysed with help of the polarizer film is therefore unknown.
Stress analysis
4.6 Conclusion
The goal of the experiments in this chapter is to determine which of the adhesive interlayer is best suitable to connect the glass panels to each other, which will result in a high load-bearing capacity of the column. Because the influence of the steel intermediary material on the moment the initial crack occurred was relatively high, it proved to be difficult to draw definitive conclusions about the most promising adhesive interlayer. Nevertheless the experiments resulted in some insights, regarding the adhesive interlayer. These insights are either related to the strength or the stiffness of the specimens. These insights are summarized below for these two aspects and the results are evaluated with respect to the other series of experiments.

4.6.1 Strength
- With an adhesive interlayer it is possible to increase the characteristic initial crack stress up to 35% for the most promising adhesive interlayer. An adhesive interlayer is able to redistribute forces and thereby avoid stress concentrations due to the tolerances on the thickness and flatness of the glass panels. Whether or not an adhesive interlayer increases the characteristic initial crack stress depends on the type of adhesive and its properties (paragraph 4.5.1).
- The method of application is an important aspect: a liquid adhesive will result in a higher characteristic initial crack stress, compared to an adhesive film as an interlayer (paragraph 4.5.1).
- The properties of the adhesive have a larger influence on the characteristic initial crack stress than the type of adhesive (i.e. acrylate, epoxy, polyurethane or acrylic) (paragraph 4.5.1).
- One of the most influential properties is the Young’s modulus of an adhesive. An adhesive with a low Young’s modulus proves to be most suitable, because the adhesive interlayer is able to redistribute the forces and thereby avoiding stress concentrations (paragraph 4.5.1).
- The difference between the characteristic initial crack stress and characteristic ultimate failure stress is quite substantial for all the specimens. This means that the columns have a large capacity to withstand loads after the first crack has occurred, resulting in a safe failure mechanism: lots of cracks are visible before the column collapses, so people can be evacuated and precautions can be made to prevent the column from collapsing. (paragraph 4.5.3).

4.6.2 Stiffness
The axial deformations are registered by the internal measurement equipment of the CTM, which are not really accurate. Nevertheless this analysis can provide some insight in the axial deformations:
- The thickness and stiffness of the adhesive interlayer are the most influential parameters for the axial deformation. The smaller the thickness and the larger the stiffness, the smaller the axial deformation will be. Because a low stiffness of the adhesive interlayer leads to a high initial crack stress, the thickness of the adhesive interlayer should be small (paragraph 4.5.2).
4.6.3 Evaluation of the results with respect to the other series of experiments
The characteristic initial crack stress of the specimens of a single glass panel (paragraph 3.4) with steel as an intermediary was 209,8 N/mm². In this chapter the highest characteristic initial crack stress was reached with an epoxy (AD821) for the adhesive interlayer. The characteristic initial crack stress was 83,0 N/mm², which is substantially lower than 209,8 N/mm². The fact that the stress is lower can be explained by the presence of horizontal compressive forces in the glass panel, due to the steel intermediary. In paragraph 3.4 a single panel was on both sides in contact with the steel intermediary. In this paragraph two glass panels were connected to each other with an adhesive interlayer and both the panels were in contact on one side with the steel intermediary. Therefore the resulting horizontal compressive forces will be smaller than for the first series of experiments (i.e. experiments A – intermediary). A typical stacked glass column will consist of lots of panels and only the top and bottom panel will be in contact with the steel intermediary. Therefore the larger the column gets, the smaller the effect of the intermediary will be, resulting in a lower initial crack stress.
Chapter 5:

EXPERIMENTS C – SMALL STACK
5 EXPERIMENTS C – SMALL STACK

The third series of experiments is into the behaviour of a small stack of five glass panels subjected to compressive loads. From the previous series of experiments it proved difficult to draw definitive conclusions about the different adhesive interlayers and its properties, because the first cracks occurred because of an imperfection in the steel intermediary blocks. The influence of the steel intermediary was therefore large compared to the influence of the adhesive interlayer. The reason a small stack of five glass panels are used in this series of experiments is to reduce the influence of the steel intermediary and to simulate the glass column in practice with multiple layers of glass. The central three glass panels in the test-specimens are not in contact with the steel intermediary so the influence of the steel will be reduced substantially. Therefore the influence of the adhesive interlayer is (relatively) larger and more definitive conclusions about the interlayer and its properties can be drawn.

5.1 Small stack-specimens

Following from the previous series of experiments, two types of liquid adhesives proved to be the most promising solution for the adhesive interlayer: Photobond 4468 (P4468) and Duopox AD821, which are both used for the next series of experiments. The first adhesive is an UV-curing, acrylate adhesive with a Young’s modulus of 250 N/mm². Duopox AD821 is a chemically curing, epoxy adhesive with a Young’s modulus of 114 N/mm². The experimental results in the previous chapter produced the insight that liquid adhesives with higher Young’s moduli would be less promising. To verify this, the polyurethane adhesive DP610 with a Young’s modulus of 800 N/mm² was also chosen for this series of experiments.

From a structural point of view the Silvertape 8502 was one of the least promising solutions for the adhesive interlayer. That is, with respect to the initial crack stress. The characteristic initial crack stress was small, but the characteristic ultimate failure stress was 356.7 N/mm². So when some small cracks will be accepted in the column, it would be possible to design a column with the adhesive film as interlayer as well. From the viewpoint of the production process the adhesive film has major advantages compared to the use of a liquid adhesive (see paragraph 4.2.2). That is the reason why Silvertape 8502 is also selected for this series of experiments.
5.2 Test setup
In this series of experiments four different adhesive interlayers, as described in the previous paragraph, are analysed. Five glass panels were connected with these different interlayers to form a small stack (fig. 5.1).

The float-glass panels have dimensions of 100 x 100 x 12 mm with ground and polished edges. The liquid adhesives have an optimum bond line thickness of 0.20 mm and the adhesive film has a thickness of 0.25 mm. Steel blocks are used as an intermediary for all the experiments. For the previous series of experiments the steel intermediary special care has been taken to make sure the panels are totally flat (by means of a milling machine (fig. 5.2)) and that the top and bottom panel are parallel to each other. The initial cracks in the previous experiments suggested that there still was some kind of imperfection in the steel intermediary. Therefore for the new series of experiments the steel blocks are mechanically ground with a whetstone to ensure no imperfections are present in the steel intermediary (fig. 5.3).

For every small stack with a different type of interlayer, five ‘identical’ experiments have been conducted to achieve a certain amount of reliability. The experiments are stopped when total failure had occurred. In order to analyze the effect of different adhesive interlayers, cracks in the two outer glass panels are neglected for the initial crack stress. Only cracks in the central three glass panels are taken into account.

The goal of this series of experiments is to determine which of the adhesive interlayers is best suitable to connect the glass panels to each other, which will result in a high load-bearing capacity of the column. Important aspects are the initial crack stress, the axial deformation and the ultimate failure stress.
5.3 Expectations

In light of the results of experiments B – interlayer the expectation is that the characteristic initial crack stress of the adhesive film will be lower than for the liquid adhesives. Furthermore the two liquid adhesives with a low Young’s modulus (i.e. P4468 and AD821) will probably result in a higher initial crack stress than the one for the adhesive with a large Young’s modulus (i.e. DP610). The difference between the two liquid adhesives, with a low Young’s modulus, will be small, so it is difficult to point out which of the liquid adhesives will be the most promising.

The difference in the characteristic ultimate failure stress of all the four adhesive interlayers are expected to be smaller than the difference of the initial crack stress. For the adhesive film the initial cracks will occur rather quickly, but ultimate failure will occur at a comparable stress as the ultimate failure stress of the liquid adhesives.

The expectation of the crack pattern is as follows. Because the surfaces of the steel intermediary are totally flat by means of mechanically grounding with a whetstone virtually no imperfections are expected. Furthermore horizontal compressive stresses will occur in the two outer panels, because of the steel intermediary. Therefore there is no reason for cracks to occur in the top and/or bottom panel of the stack. The compressive forces will not be present (or substantially smaller) for central three panels, because they are not in direct contact with the steel intermediary and the stiffness of the interlayer is small (except for the polyurethane adhesive DP610): the interlayer cannot transfer these horizontal compressive forces from the top/bottom panel to the central panels. Therefore it is expected that the initial crack will occur in one of the three central panels.

For the polyurethane adhesive DP610, with a high Young’s modulus, the expectation is that the initial crack will occur also in one of the central three panels. Because of the higher Young’s modulus the adhesive interlayer can transfer some of the horizontal compressive forces to the central panels, but they will be lower than for the two outer panels.
5.4 Results

5.4.1 Initial crack

As described in paragraph 5.2 the experiments were stopped when ultimate failure occurred. Nevertheless the stress at the moment of the initial crack can also be measured.

The expectation was that the initial crack stresses of the adhesive film would be lower than for the liquid adhesives. The results (fig. 5.4, table 5.1 and Appendix G) show however that the specimens with the adhesive film had the highest initial crack stress, which is entirely contradicting with the results in the previous chapter. The small stacks of five panels however are more comparable to the glass column in practice which is build up out of hundreds of panels. This aspect and the fact that in the previous chapter the influence of irregularities in the steel intermediary played a substantial role, make the results in this chapter more reliable.

The results do correspond with the expectations regarding to the liquid adhesives. The initial crack stresses of the liquid adhesives with a low Young’s modulus (i.e. P4468 and AD821) were comparable and substantially larger than the initial crack stress of the liquid adhesive with a high Young’s modulus (i.e. DP610). These results also correspond with the results in the previous chapter.

5.4.2 Axial deformation

As discussed before the axial deformations are another relevant aspect for the glass column: when the axial deformations become too large the top point of the columns lowers too much to act as a bearing for other structural elements, because the other building components (like beams or floors) cannot be assembled perfectly horizontal.

Table 5.2 shows the axial deformations at a stress from 1 to 50 N/mm². The value of 1 N/mm² is because of the settings of the CTM and at stresses higher than 50 N/mm² the relationship between the load and deformation is linear.
Table 5.3 shows the additional deformation at a stress from 50 to 135 N/mm². The force-displacement relationship is linear over this trajectory and the value of 135 N/mm² is chosen so that all specimens reach this stress. The deformations are registered by the internal measurement equipment of the CTM, which are not really accurate. So for definitive conclusions the deformations should be measured with more accurate measurement devices. Nevertheless this analysis can provide some insight in the axial deformations.

From table 5.2 and table 5.3 it becomes clear that both the initial and additional axial deformations are the highest for the acrylate adhesive and the lowest for the adhesive film. With respect to the axial deformation the adhesive film would be the most promising interlayer material.

A closer look at the data for the acrylate adhesive shows that the average initial and additional axial deformations are a little bit higher compared to the other adhesive interlayers, but that the standard deviation is relatively high, which results in larger characteristic axial deformations. The difference in the stiffness of the specimens with P4468 as an adhesive interlayer is relatively high, hence the large standard deviation. This can only be explained by a large difference in stiffness of the adhesive interlayer, because the stiffness of the glass panels is more or less equal. This suggests that something some more attention needs to be paid to the UV-curing of the adhesive interlayers. During production the time of irradiation and the distance between the specimens and the UV-lamp were kept exactly identical, but still the intensity of irradiation, which was not measured during curing, was probably different for the different specimens. The intensity is not only dependent on the time of irradiation and the distance between the lamp and the specimen, but also on the time the UV-lamp needs to warm up. Although the minimum time of three minutes was taken into account for the first specimen, it would be possible that the intensity during curing of one of the last specimens is higher: the lamp has been used frequently before and thus had more time to warm up. When further research is conducted into the use of UV-curing adhesives it is therefore advised to measure the intensity of the UV-light during curing. Special equipment is available for this and the manufacturers are confident that adhesive interlayers with identical stiffness can be reached. [24]

<table>
<thead>
<tr>
<th>Table 5.1 Test-results experiments C – Small stack (initial crack)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interlayer</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>P4468 (AC)</td>
</tr>
<tr>
<td>AD821 (EP)</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
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<tr>
<td>DP610 (PU)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.2 Test-results experiments C – Small stack (initial axial deformation at a stress from 1 to 50 N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interlayer</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>P4468 (AC)</td>
</tr>
<tr>
<td>AD821 (EP)</td>
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<tr>
<td>ST8502 (AF)</td>
</tr>
<tr>
<td>DP610 (PU)</td>
</tr>
</tbody>
</table>
5.4.3 Ultimate failure

All the experiments were stopped when ultimate failure occurred (table 5.4). In the previous chapter it became clear that at ultimate failure the specimens virtually explode and the only thing what was left of the specimens was glass crumbles. For the specimens with a liquid adhesive as an interlayer in this series of experiments this also holds true.

However for the adhesive film something else happens. The compression testing machine automatically shuts down when the load drops abruptly and/or the displacements increase abruptly (i.e. in this case when the load drops, because the experiment is load-controlled). And that is exactly what happens for the adhesive film: when the initial crack occurs, cracks occur instantly over the entire surface of one or multiple glass panels, which results in ultimate failure: the load drops abruptly and because of that, the compression testing machine shuts down. This is contradictory with the initial crack of the specimens with a liquid adhesive where the initial crack is a small crack in one of the glass panels. Therefore the load does not drop and subsequently the compression testing machine does not shut down. The abrupt drop in load is unwanted for a glass column and therefore can be defined as ultimate failure: subsequently the characteristic initial crack stress is identical to the characteristic ultimate failure stress for the adhesive film. These results are also entirely contradicting with the results in the previous chapter, where an initial crack occurred at a low stress and ultimate failure occurred at a higher stress for the adhesive film. The results, regarding the adhesive interlayer, in this chapter are expected to be more reliable, because of the smaller influence of imperfections in the steel intermediary.

When the characteristic ultimate failure stress of the different specimens are compared the epoxy AD821 and/or the polyurethane adhesive DP610 are the most promising adhesives (table 5.3). The average ultimate failure load of the acrylate adhesive P4468 is just a little bit lower, but a large standard deviation results in a lower characteristic ultimate failure stress. The adhesive film appears to be the least promising adhesive. The expectation was that the ultimate failure stress would be more or less equal for all the interlayer specimens, but the results show that substantial differences do occur, especially because the initial crack load of the adhesive film is identical to the ultimate failure load.

<table>
<thead>
<tr>
<th>Interlayer</th>
<th>Average ultimate failure load $m_{u,i}$ [kN]</th>
<th>Standard deviation $s_{m,i}$ [kN]</th>
<th>Characteristic ultimate failure load $F_{u,i}$ [kN]</th>
<th>Characteristic ultimate failure stress $\sigma_{u,i}$ [N/mm$^2$]</th>
<th>Percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P4468 (AC)</td>
<td>-2163,0</td>
<td>302,4</td>
<td>-1618,8</td>
<td>-161,9</td>
<td>74,6</td>
</tr>
<tr>
<td>AD821 (EP)</td>
<td>2366,8</td>
<td>108,5</td>
<td>-2171,4</td>
<td>-217,1</td>
<td>100,0</td>
</tr>
<tr>
<td>ST8502 (AF)</td>
<td>1527,4</td>
<td>75,5</td>
<td>-1391,5</td>
<td>-139,2</td>
<td>64,1</td>
</tr>
<tr>
<td>DP610 (PU)</td>
<td>2351,2</td>
<td>115,6</td>
<td>-2143,0</td>
<td>-214,3</td>
<td>98,7</td>
</tr>
</tbody>
</table>

Table 5.3 Test-results experiments C – Small stack (additional axial deformation at a stress from 50 to 135 N/mm$^2$)
5.4.4 Crack analysis

Ultimate failure has occurred for all the test specimens and the only thing that was left of the specimens were glass crumbles for both the liquid adhesives. For the acrylic film a dense crack pattern over the entire surface is noticeable at the moment the initial crack/ultimate failure occurs.

The fact in which of the panels the (initial) cracks occur is more interesting to analyze. The expectation was that the initial crack would occur in one of the three central panels. That is, if there would be no imperfections in the surface of the steel intermediary. In figure 5.5 it becomes evident that the expectations were right. The figures show all the cracks before total failure of one of the specimens with P4468, AD821 and DP610 as an adhesive interlayer (the other specimens showed similar crack patterns). In general the initial crack (top figures in figure 5.5) and the following cracks occur in the central three panels. Only just before ultimate failure (bottom figures in figure 5.5) also cracks occur in the outer two panels. In two cases with DP610 as an intermediary cracks occurred also in one of the outer panels, probably because of some defect in the glass panel.

Another important aspect which becomes visible in these figures: the cracks which occur in these specimens only occur at the edges of the relevant glass panel not over the entire surface. For example: in the top left figure it is visible that the initial crack for the specimen with P4468 as an intermediary occurs at the back edge of the second panel (counted from the bottom). In the third figure cracks occur in the same panel (i.e. second panel counted from the bottom) but this time at the front edge of the panel.
The crack patterns for the specimens with an adhesive film as an adhesive interlayer show similarities, but also differences:

The cracks occur in two or three central panels and the two outer panels show no cracks at all (fig. 5.6). This is a similarity between the crack pattern of the adhesive film and the liquid adhesives.

An important difference is that the initial crack occurs more or less at the same time in two or three central panels and also occurs over the entire surface. Because the entire surface cracks in an instant, the load abruptly drops so that the compression testing machine shuts down automatically. That is the reason that the characteristic initial crack stress is identical to the characteristic ultimate failure stress for the adhesive film. This result suggests that the adhesive film is not able to slow down the crack growth, whereas the liquid adhesive is able to do this.

Another important aspect is that (virtually) no cracks occur in the outer panels for both the adhesive film and the liquid adhesives. Therefore it can be concluded that mechanically grounding the steel intermediary blocks with a whetstone results in a totally flat surface.
5.4.5 Stress analysis

In figure 5.7 the stresses are shown for the specimens with different adhesive interlayers up until the initial crack. The stress distribution is comparable to the stresses in the first series of experiment (i.e. Experiments A – intermediary) for steel as an intermediary: the dark part grows from the vertical center of the specimens to the contact surfaces between glass and steel. This however was not the case in Experiments B – interlayer. In those series of experiments the stress distribution was more comparable to the stress distribution of Experiments A with aluminium as an intermediary, even though steel was used as an intermediary. What would be the explanation for this phenomenon is unknown.

When the stress distributions of Experiments C – Small Stack are compared to each other, it can be concluded that the stress distributions with the liquid adhesives as an interlayer are quite similar. The dark part grows from the horizontal center to the contact surfaces between glass and steel. The only difference between these stress distributions is that for epoxy AD821 lighter spots begin to emerge at a higher load somewhere in the central panels (sixth figure in the center). The lighter spots coincide with position of the initial crack. However for only two of the five specimens these lighter spots emerged. For the other three specimens the initial crack occurred without lighter spots to emerge in the stress distribution.

The stress distribution of the specimens with the adhesive film as interlayer is a little bit different. The dark area does not grow from the center of the specimen but emerges gradually over the entire specimen. In these specimens also lighter spots emerge at a higher load. In this case however the light spots emerge also over the entire surface, but they are mostly concentrated in the central three panels. The initial crack also occurs in multiple of these three central panels, so the lighter spots also more or less coincide with the position of the initial crack.

In the previous series of experiments there was no link between the stress distribution and the position of the initial crack. The focus of the first series of experiments was at what position the cracks occurred over the surface of one or two glass panels. In this series of experiments the focus lies on which of the five panels cracks first. This is a different approach and the reason in this series of experiment, in some cases (i.e. specimens with AD821 and ST8502 as an interlayer), a link is visible between the stresses and the position of initial crack (the spots which light up just before the initial crack occurs).
Stress analysis

C02 - P4468 (AC)  C07 - AD821 (EP)  C11 - ST8502 (AF)  C20 - DP610 (PU)

- 0.0 N/mm²
- 0.0 N/mm²
- 0.0 N/mm²
- 0.0 N/mm²
- 1.3 N/mm²
- 1.1 N/mm²
- 0.4 N/mm²
- 0.0 N/mm²
- 3.1 N/mm²
- 2.4 N/mm²
- 1.2 N/mm²
- 0.6 N/mm²
- 9.1 N/mm²
- 3.8 N/mm²
- 6.4 N/mm²
- 0.2 N/mm²
- 4.7 N/mm²
- 5.3 N/mm²
- 6.9 N/mm²
- 0.2 N/mm²
- 10.4 N/mm²
- 16.2 N/mm²
- 31.6 N/mm²
- 0.3 N/mm²
- 17.1 N/mm²
- 165.9 N/mm²
- 163.4 N/mm²
- 108.2 N/mm²
- 171.5 N/mm²
- 166.3 N/mm²
- 153.7 N/mm²
- 168.7 N/mm²

5.7
5.5 Conclusion

The goal of the experiments in this chapter is to determine which of the adhesive interlayers is best suitable to connect the glass panels to each other, which will result in a high load-bearing capacity of the column. With help of the results of the experiments in this chapter, the insights which became visible from the previous series of experiments (i.e. experiments B – interlayer) are evaluated. It proved to be difficult to draw definitive conclusions from those experiments, because the influence of the steel intermediary (with minor irregularities) was too large. In this chapter the steel intermediaries were totally flat, because of a different production technique and furthermore the influence of the steel intermediary was smaller because a small stack of panels were used instead of two glass panels. The conclusion which can be drawn from these experiments can be categorized into three main aspects: strength and stiffness and conclusions regarding to the crack and stress analysis.

5.5.1 Strength
- In the previous chapter it appeared that a liquid adhesive would result in a higher initial crack stress, compared to an adhesive film as an interlayer. The results in this chapter however show an opposite behaviour: the characteristic initial crack stress for the adhesive film was 35% to 85% higher than for the liquid adhesives. These results are more reliable, because influence of the steel intermediaries used in the experiments for this chapter was smaller, because they were totally flat and a stack of 5 panels has been used. That a specimen with an adhesive film results in a higher initial crack stress can be explained by the fact that the adhesive film does not cure. The adhesive film remains entirely flexible, so loads can be redistributed and stress concentrations are avoided.

- A second aspect which became visible in the previous chapter was that a liquid adhesive with a low Young’s modulus would be more promising than one with a high Young’s modulus. The results in this chapter validate this, because the characteristic initial crack stress of both P4468 (E=250 N/mm²) and AD821 (E=114 N/mm²) were approximately 35% higher than the characteristic initial crack stress of DP610 (E=800 N/mm²).

- The difference between the characteristic initial crack stress and characteristic ultimate failure stress was quite substantial for all the specimens in the results of the previous chapter. The results for the liquid adhesives in this chapter show the same behaviour, but the results of the adhesive film show an opposite one: at the moment the initial crack occurs multiple central panels are cracked over the entire surface and ultimate failure occurs. The initial crack stress and the ultimate failure stress is therefore identical, which results in a non-safe failure behaviour for columns with an adhesive film as interlayer. Apparently the adhesive film is not able to slow down crack growth. The liquid adhesive can slow down crack growth, because it forms a strong (chemical) bond, and therefore the specimens with a liquid adhesive as interlayer do have a safe failure behaviour: the ultimate failure stresses are respectively 61%, 115 % and 185% larger than the initial crack stress. Lots of cracks are visible before the column collapses, so people can be evacuated and precautions can be made to prevent the column from collapsing.
5.5.2 Stiffness
The axial deformations are registered by the internal measurement equipment of the CTM, which are not really accurate. Nevertheless this analysis can provide some insight in the axial deformations:

- The axial deformations and the standard deviation on the axial deformations are relatively large for the UV-curing acrylate adhesive. From this it can be concluded that there is a large deviation in the stiffness of the acrylate interlayer. Although precautions have been made to ensure that the intensity of the UV-light during curing are more or less equal (i.e. identical irradiation time and distance between the lamp and the specimen) there is a large deviation in the stiffness of the interlayer. When further research is conducted into the use of UV-curing adhesives it is therefore advised to make use of special equipment to measure the intensity of the UV-light during curing.
- The axial deformations of the specimen with the adhesive film is 7 to 30% smaller, compared to the axial deformation of specimens with the epoxy and polyurethane and even 46 to 89% smaller than the axial deformation of the specimen with the UV-curing acrylate adhesive. So from this point of view an adhesive film would be the most promising type of glue for the adhesive interlayer.

When the aspects with respect to the strength and stiffness are combined the epoxy adhesive AD821 is the most promising type of glue for the adhesive interlayer: it has a relatively high characteristic initial crack stress, a characteristic ultimate failure stress which is 115% higher than the characteristic initial crack stress and a reasonably low axial deformation.

5.5.3 Crack and stress analysis
As was expected the initial crack occurred, in general, in one of three central panels. From this the presence of horizontal compressive forces in the top/bottom glass panels is confirmed (again). Only for 2 specimens (with an adhesive with a higher Young’s modulus) the initial crack occurred in one of the outer panels. What is furthermore interesting is that in some cases the position, where the initial crack was about to occur, lighted up due to the polarizer film. So in the figures of the stress distribution the position with the highest tension stresses become visible. This is interesting because this could be used as a non-destructive quality control for stacked glass columns in the future.
Chapter 6:

EXPERIMENTS D – LARGE STACK
6 EXPERIMENTS D – LARGE STACK

The fourth series of experiments is into the behaviour of a large stack of twenty glass panels subjected to compressive loads. It would be interesting to see if there is a difference in the initial crack load and/or ultimate failure stress between a small stack of five panels and a large stack of twenty panels. The column is only as strong as the ‘weakest link in the chain’. The standard deviation of the strength of glass panels is quite large and the chance that a weaker glass panel is used in the column is larger when more panels are used. Therefore a larger stack will result in a lower initial crack stress and/or ultimate failure stress. Furthermore it would be interesting to analyze how the cracks propagate through the specimen. Will the cracks concentrate in one or multiple adjoining glass panels which results in total failure of these panels, while the other panels remain intact? Or will small cracks occur in all the glass panels, before one or multiple panels will fail totally?

6.1 Large stack-specimens

In the previous series of experiments epoxy adhesive AD821 with a Young’s modulus of 114 N/mm² proved to be the most suitable glue for an adhesive interlayer. In addition to the specimen with AD821 as an intermediary (fig. 6.1) also one specimen with the adhesive film ST8502 is analysed in this chapter (fig. 6.2). The production process of a column with an adhesive film is quick and easy. Furthermore in previous experiments the results of two panels and a stack of five panels, both with ST8502 as an interlayer, were quite contradicting. Therefore an additional test with a stack of twenty panels would be useful.
6.2 Test setup

In this series of experiments two different adhesive interlayers, as described in the previous paragraph, are analysed. Twenty panels were connected with these two interlayers to form a large stack of glass panels (fig. 6.3).

The float-glass panels have dimensions of 100 x 100 x 12 mm with ground and polished edges. The liquid adhesives have an optimum bond line thickness of 0,20 mm and the adhesive film has a thickness of 0,25 mm. Steel blocks are used as an intermediary for all the experiments. The steel blocks are mechanically grounded with a whetstone to ensure no imperfections are present in the steel intermediary.

For every large stack with a different type of interlayer only one ‘identical’ experiment has been conducted. It is impossible to do statistical interpretations for this one specimen, so it is not possible to calculate a characteristic initial crack stress or ultimate failure stress as for the experiments in the other chapters. It however is possible to compare these results with the results in the previous series of experiments.

The goal of this series of experiments is to determine whether or not the large standard deviation in the strength of glass panels leads to a lower initial crack stress and/or ultimate failure stress (i.e. the ‘weakest link in the chain’-effect). Another goal is to determine in which panel or panels the initial crack will occur and how the cracks will propagate through the specimen.
6.3 Expectations

First of all the expectation is that both the initial crack stress and the ultimate failure stress will be a little bit lower for the specimens with both the adhesive interlayers. This has two reasons. First of all the stress will probably be lower because of the ‘weakest link in the chain’-effect. The chance that a glass panel with a low strength or some kind of defect is present in a large stack is larger. Secondly the horizontal compressive forces in the glass panels because of the steel intermediary are lower.

For the small stack of five panels these compressive forces in the central panel are limited (if not zero), but for the large stack of twenty panels it is safe to say that the horizontal compressive forces in the central panel(s) are definitely zero. These two phenomena will probably result in a lower initial crack stress and ultimate failure stress compared to the results for the small stacks.

As for the crack propagation the results in the previous chapter suggest that there will be a substantial difference between the two types of adhesive interlayer:

For the liquid adhesive AD821 the initial crack will occur in one of the central panels (because the presence of horizontal compressive forces in the top/bottom panels), but in which of these central panels might depend on the some kind of defect in one particular panel (because of the ‘weakest link in the chain’-effect). With ‘one of the central panels’ actually a large range of central panels is meant, not the most central panel. Because of the low Young’s modulus of the adhesive interlayer the horizontal compressive forces will decrease exponentially the further away the panel is from the contact surface with the steel intermediary. So with ‘one of the central panels’ the ten to fifteen most central panels are meant.

The initial crack is expected to be a minor crack in one of the central panels and then probably another small crack will occur somewhere else in another central panel and so on. Therefore lots of small cracks will occur in the central panels and these small cracks will probably grow into larger cracks until one or multiple central panels will ‘explode’ which results in ultimate failure.

For the specimen with the adhesive film as an interlayer the expectation is that something else will happen. The initial crack will occur in one of the ten to fifteen most central panels, but in which particular panel might depend on a defect in one of the panels. In the previous chapter it became clear that the liquid adhesive can slow down crack growth, whereas the adhesive film is not able to do this. Subsequently the initial crack for the specimen with an adhesive film as intermediary will result in a dense crack pattern for one or multiple of these central panels. Because of the dense crack pattern the load will drop abruptly so that the compression testing machine shuts down automatically. The initial crack stress will therefore be identical to the ultimate failure load.

Which of the two specimens will result in a higher initial crack stress is difficult to predict, because in this chapter only one ‘identical’ experiment is conducted per type of adhesive interlayer. In the previous chapter the initial crack stress for the specimen with AD821 as interlayer ranged from 138,3 N/mm² to 243,1 N/mm². The initial crack stress for the specimens with the adhesive film ST8502 as interlayer showed a smaller range: 139,7 N/mm² to 158,6 N/mm². Because of the large standard deviation in the results it is difficult to predict which specimen will have a higher initial crack stress.

For the ultimate failure load a prediction can be made: the initial crack stress and ultimate failure load for the adhesive film will be identical. The ultimate failure load of the liquid adhesive ranged from 220,5 N/mm² to 250,5 N/mm² in the previous series of experiments. Based on these results the ultimate failure load for the specimen with the liquid adhesive will be substantially higher, than for the specimen with the adhesive film.
6.4 Results

6.4.1 Initial crack

It is difficult to predict which of the two specimens will result in a higher initial crack stress because only one experiment per type of interlayer is conducted and the standard deviation between the identical experiments in the previous series of experiments was quite large. The results of the experiments in this chapter show that the initial crack stresses of the two specimens were approximately identical: 108,1 N/mm² for the liquid adhesive AD821 and 110,8 N/mm² for the adhesive film ST8502 (fig. 6.4). These values are initial crack stresses of only one experiment, so it is not the characteristic initial crack stress resulting from statistical interpretation like in the previous series of experiments. The values of the initial crack stress for both the liquid adhesive as the adhesive film are lower than the lowest value for those types of interlayer in the previous chapter. Therefore the characteristic initial crack stress for the large stacks will in all probability be lower, compared to the characteristic initial crack stress for the small stack.

6.4.2 Axial deformation

As for the axial deformations the liquid adhesive is a little bit more suitable (fig. 6.4): the specimen with the liquid adhesive had an initial axial deformation (1 to 50 N/mm²) of 0,59mm versus 0,71mm for the adhesive film. The additional axial deformations (between 50 and 105 N/mm²) were 0,50mm for the liquid adhesive versus 0,61mm for the adhesive film. These values are based on one experiment and thus do not result from any statistical interpretation.

6.4.3 Ultimate failure

For the ultimate failure of a large stack a similar behaviour is visible as for the small stack. The initial crack stress and ultimate failure stress are identical for the specimens with adhesive film as interlayer, whereas the ultimate failure load for the specimen with the liquid adhesive as interlayer is higher than the initial crack stress.

Furthermore the characteristic ultimate failure stress for the large stack will probably be lower than for the small stack: the values of the ultimate failure stress for both the liquid adhesive and the adhesive film are lower than the lowest value for those types of interlayer in the previous chapter.
6.4.4 Crack analysis

The expectation for the crack propagation of the specimen with the liquid adhesive AD821 as an interlayer was that the initial crack would occur somewhere in the central ten to fifteen panels and would be small.

The results of this experiment seem to verify these expectations (fig. 6.5). The initial crack occurred in one of the most central glass panels and it was only a small crack. Then the second crack was a small crack in the same panel at another position. The third crack was a small crack two panels from the top panel, so probably this panel had some kind of defect. The next cracks which occurred accumulated around the central eight to ten panels, and some minor cracks were visible in some of the other panels. The central eight to ten panels were almost entirely cracked at the point some of these central panels ‘exploded’ and ultimate failure had occurred.

For the specimen with the adhesive film as interlayer the expectation was that the initial crack would occur somewhere in the central ten to fifteen panels and that the initial crack would be quite large, which immediately results in total failure of the specimen.

The expectations are partially verified. The initial crack is relatively large and subsequently resulted in total failure of the specimen. The location of the initial crack is however not entirely as was expected. The initial crack occurred in the fifth panel from the top and immediately the fourth, third and second panel from above also cracked entirely. These cracks are visible in the upper figure of figure 6.6. The expectation was that the initial crack would be more in the center of the panel. The top most glass panel remained intact. This seems to indicate that horizontal compressive forces are present in the top most panel, but not in the following panels. It appears that the adhesive film is not able to transfer any forces from the first glass panel to the other glass panels. This corresponds with the fact that the adhesive film is not able to slow down the crack growth.

When the initial crack occurred in the second to the fifth panel from the top, the load abruptly
dropped and the compression testing machine has automatically been shut down. This can be defined as ultimate failure of the large stack, but the top panel and the bottom fifteen panels are still entirely intact, so the column will have some residual capacity. To see whether or not the specimen had some residual capacity the same specimen is loaded again by the compression testing machine (fig. 6.6). The initial crack occurred at a stress of 110.8 N/mm². When the same specimen was loaded for the second time a large crack occurred in the sixth panel from the top and immediately the seventh to thirteenth panel also cracked. Subsequently the load dropped abruptly again and the compression testing machine has been shut down. This all happened at a stress of 42.8 N/mm². This procedure is repeated one more time and this time the cracks occurred only in the fourteenth panel at a stress of 26.0 N/mm². This procedure of loading the column repeatedly from zero to the ultimate failure load is entirely different from how the column will fail in practice. In practice the column will reach a point where one panel cracks (for whatever reason) the external load will always remain on top of the column. In this experiment the external load drops when the compression testing machine shuts down. In practice one panel after the other will fail, like we saw for a few panels in the experiment. In practice however the cracking of the panels will not stop after a few panels, but will go on until all the panels are cracked, which results in ultimate failure of the entire column.

The crack analysis shows that the specimens with the two different types of adhesive interlayers have a different failure behaviour, which can be explained by the ability of the adhesive interlayer to slow down the crack growth. The liquid adhesive is able to slow down crack growth and thus an initial crack does not result in ultimate failure of the column. The adhesive film cannot slow down crack growth and an initial crack results in progressive collapse of the other glass panels and subsequently in ultimate failure of the column.
6.4.5 Stress analysis

In the previous chapter the position where the initial crack was about to occur lighted up before the actual crack had occurred. This could be used as a non-destructive quality control for stacked glass columns. In this chapter this phenomenon is partially confirmed: in the top figures of figure 6.7 the center of the column with the liquid adhesive as an interlayer clearly lights up, when viewed through the polarizer film. When the stress is at only 10% of the initial crack stress the position where the initial crack will occur can be defined in the figures.

For the specimen with the adhesive film as an interlayer the exact position, where the first crack will occur, is not as clearly visible as for the specimen with the liquid adhesive as an interlayer. In these figures some bright spots light up over the entire column, but they seem to be concentrated in the top few panels and the bottom few panels. The top few panels are the panels in which the initial crack had occurred. For the second and the third crack, after starting new loading-cycles, the position of the upcoming crack is more clearly visible (fig. 6.8). The panels just below the already cracked panels light up and the closer the panel is from the already cracked panels the larger the bright spot is. From this is can be concluded that with these types of adhesives the position where the initial crack will occur can be defined, especially for the liquid adhesive. It however is not possible to predict at which stress the panel will fail. So only the position can be defined, not whether or not the column is about to fail. As described the polarizer film could be used for a non-destructive quality control, but only a qualitative control, not a quantitative one.
STABILITY

Another aspect came to light during the stress analysis which actually has no direct relationship with the stresses: instability problems, although in this case it is not (Euler) buckling in the traditional sense of the phenomenon. (Euler) buckling normally plays a role in slender columns, so the ‘columns’ of one, two or five glass panels are not susceptible for buckling. Even specimens of 20 panels, with a slenderness of 8, are not expected to be susceptible for buckling. However for the specimen with the adhesive film as an interlayer something was noticeable which points to an instability problem: the center of the column sways to the left in the last two figures (fig. 6.7). In this case it is not really (Euler) buckling, but more like a central glass panel is pushed out of the layered column due to horizontal forces. During production some degree of flexibility was already noticeable in the large stacked column with the adhesive film as interlayer: the top panel could be rotated a little bit in relation to the bottom panel. The column with the adhesive film as an interlayer therefore appeared as a layered element, whereas the column with the liquid adhesive AD821 appeared to be more or less solid. In the figures for the stress analysis of AD821 no buckling is visible. The central panel just cracks. From this it appears that the column with the adhesive film as an interlayer is more susceptible for buckling, than the column with the liquid adhesive as an interlayer. This phenomenon can be explained by the fact that the adhesive film does not really cure. There is no strong (chemical) bond between the interlayer and the glass panels and therefore the glass panel can roll over the adhesive interlayer. This is yet another reason that the epoxy AD821 is the most promising type of adhesive for the stacked column.

![D2 – ST8502 (AF) – second crack](image1)

![D2 – ST8502 (AF) – third crack](image2)

Stress analysis | 84
6.5 Conclusion
The experiments conducted in this chapter again confirm that the epoxy AD821 is the most promising type of adhesive for a stacked column with an adhesive interlayer. Next to conclusion about the strength and stiffness, by means of the results of the experiments in this chapter a conclusion can be drawn for the stability of the column. The crack and stress analysis furthermore resulted in some relevant conclusions.

6.5.1 Strength
- The initial crack stress for the two types of interlayers is comparable, but when some cracks will be accepted for the stacked column, the epoxy AD821 is the most promising. This type of interlayer is able to slow down crack growth and therefore the initial crack and also some of the following cracks are quite small, which could be accepted. Whether or not cracks need to be accepted, and to what extent, is a matter of aesthetics and a question, which falls beyond the scope of this graduation project.
- The ultimate failure stress for the specimen with AD821 as an interlayer is relatively large, compared to the ultimate failure stress for the specimen with the adhesive film as an interlayer. What’s furthermore important is that the specimen with AD821 as an interlayer exhibits a safe failure behaviour: the specimen with this type of adhesive has a large post-initial crack strength, because it is able to slow down crack growth.

6.5.2 Stiffness
The axial deformations are registered by the internal measurement equipment of the CTM, which are not really accurate. Nevertheless this analysis can provide some insight in the axial deformations:
- As for the axial deformations the liquid adhesive is a little bit more suitable, although the differences are minimal: the specimen with the liquid adhesive had an initial axial deformation (1 to 50 N/mm²) of 0,59mm versus 0,71mm for the adhesive film. The additional axial deformations (between 50 and 105 N/mm²) were 0,50mm for the liquid adhesive versus 0,61mm for the adhesive film These values are based on one experiment and thus do not result from any statistical interpretation.

These findings are contradictory to the findings in the previous series of experiments, where the adhesive film would be more suitable as for the axial deformations are concerned. Additional research with more accurate measurement equipment would be necessary to draw conclusion as for the best interlayer material regarding the stiffness of the column.

6.5.3 Stability
- A third aspect which was not a topic of discussion in the previous chapters and series of experiments is stability. Columns with a slenderness of 8 are not expected to be susceptible to buckling. However, during the last experiment the center of the large stack with the adhesive film as an interlayer swayed to the left. Although this is not (Euler) buckling in the traditional sense of the phenomenon it points to instability problems. In this case it’s more like a central glass panel is pushed out of the layered column due to horizontal forces. The adhesive film does not cure and does not form a strong (chemical) bond with the glass panels and thus the column appears as a layered element. The liquid adhesive AD821 does cure and does form a strong (chemical) bond which results in a more or less solid element. From this it can be concluded that stacked glass columns with adhesive films as an interlayer are more susceptible for instability problems.
6.5.4 Crack and stress analysis

Another goal for these experiments was to determine in which panel or panels the initial crack(s) will occur and how the cracks will propagate through the specimen.

- The initial crack for the specimen with AD821 as an adhesive interlayer occurred in one of the most central glass panels and it was only a small crack. The next cracks which occurred accumulated around the central eight to ten panels, and some minor cracks were visible in some of the other panels. The central eight to ten panels were almost entirely cracked at the point some of these central panels ‘exploded’ and ultimate failure had occurred.
- The initial crack for the specimen with adhesive film ST8502 occurred in the fifth panel from the top. This panel was cracked entirely and immediately the fourth, third and second panel from above also cracked entirely, which resulted in total failure of the specimen.

From this it can be concluded that the influence zone of the intermediary is limited to the first (few) panels on the top/bottom of the glass column and the central panels will fail before the top/bottom panel(s) will fail. For a large stacked column, build up out of hundreds of glass panels, it might be beneficial to use aluminium as an intermediary. Aluminium has approximately the same Young’s modulus as glass and therefore no horizontal tension-stresses will occur in the glass panels. Because the Young’s modulus of aluminium is only one-third of the Young’s modulus of steel, the presence of irregularities (in the surfaces of the materials or external irregularities like sand for instance) is not as big as a problem as for steel: aluminium will deform, so no cracks will occur in the glass panels.

Another aspect which became visible in the crack and stress analysis is the fact that the polarizer film could be used for a non-destructive quality control. It however is not possible to predict at which stress the panel will fail. So only the position can be defined, not whether or not the column is about to fail. Therefore the non-destructive quality control is only of a qualitative nature, not a quantitative one. Nevertheless this finding is interesting and maybe this procedure can be developed into a quantitative control as well by means of future research.

6.5.5 Evaluation of the results with respect to the other series of experiments

Another goal of the experiments in this chapter was to determine whether or not the large standard deviation in the strength of glass panels leads to a lower initial crack stress and/or ultimate failure stress (i.e. the ‘weakest link in the chain’-effect).

Because only a single experiment has been conducted per adhesive interlayer, the characteristic initial crack stress and characteristic ultimate failure stress can’t be calculated. However, it is safe to say that both these values will be a lower for the large stacks than for the small stacks: the values of these stresses for both the liquid adhesive as the adhesive film are lower than the lowest value for those types of interlayer in the previous chapter. Therefore the resulting characteristic failure stresses for a column build up out of hundreds of glass panels will be lower than the values presented in this chapter and the previous chapter.
PART 2.2: NUMERICAL RESEARCH
THE STACKED COLUMN
Chapter 7:
NUMERICAL RESEARCH
7 NUMERICAL RESEARCH
From the first series of experiments into the intermediary materials, a wide variety in crack patterns at failure were noticeable. This suggests that the stresses in the glass panels with different intermediaries differ quite a lot. In order to gain more information about these stresses and the resulting crack pattern some exploratory numerical research is conducted. These Finite Element Models are built by Fred Veer from Delft University of Technology in ANSYS V14.0.

7.1 Finite Element Model setup
The goal of numerical research is to provide information about the stresses in the glass panels at the end of the experiments described in chapter 3. A first order elastic calculation has been carried out, to provide some information about the stresses. In some cases plastic deformation plays a role, for instance for the deformations with POM as an intermediary, but because of the exploratory nature of the numerical research only a first order elastic calculation has been carried out to prevent the numerical research from getting too complex.

GEOMETRY
Because of the symmetry in the experiments it is sufficient to model only 1/8th of the specimens, which reduces the calculation-time substantially. The part which is modelled in ANSYS is shown in figure 7.1. Obviously the total dimensions are equal to dimensions of the specimens in chapter 3 Experiments A – intermediary.

ELEMENT TYPE
Because different materials (with different material properties) are used the elements should be able to simulate both small and large deformations. Therefore a universal element type is chosen for this numerical model: SOLID185 (cubic). SOLID185 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions (figure 7.2).

On the contact-surface between the different materials the choice has been made to model this surface without contact elements. The numerical research presented here is only of exploratory nature and the goal is get insight in the stresses at the end of the experiments, which is a static
situation. Furthermore the friction in the contact-surface is difficult to model, partly because the friction is dependent on the compression-force on the specimens. To get some exploratory information about the stresses in the glass panels it is assumed to be sufficient to model the contact-surface without contact elements.

**MATERIAL PROPERTIES**

The material properties which are used in the Finite Element Model are summarized in table 7.1. Some of the values for the material-properties differ a little bit from the values presented in paragraph 3.1. However the differences are minimal, and will not lead to substantial differences in the stresses in the glass panels. From the two plastics (POM and Nylon) only POM has been modelled, because the material properties which are used in these models are more or less equal for POM and Nylon.

**MESHING**

For the meshing an orthogonal grid can be used. Over the length and width of the specimens (figure 7.1) the mesh is equal for all different materials and consist of a minimum of 10 elements, where both the length and width have absolute dimensions of 50 mm. The steel blocks consist of a minimum of 12 elements over the thickness (which has an absolute thickness of 60 mm). For glass a finer mesh is chosen: a minimum of 5 elements are used over the thickness, which measures 6 mm (i.e. half thickness of the glass panel). For rubber, POM and aluminium respectively 15, 12 and 8 elements are used over the thickness. A total overview of the meshes is presented in appendix H.

**LOADS**

A non-zero displacement is assigned to some nodes in the model to simulate the displacement at moment of initial crack in the experiments of chapter 3. The imposed displacements are in accordance with the test specimen which had the lowest initial crack stress (i.e. and also the lowest displacement) out of the five ‘identical’ experiments. For the model with steel as an intermediary the imposed displacement is 0,5 mm. Due to symmetry the total imposed displacement would be 1,0 mm which is equal to the displacement of Exp. A02 at the moment of initial crack. For rubber, POM and aluminium imposed displacements are assigned of respectively 12,5 mm, 1 mm and 0,5 mm.

<table>
<thead>
<tr>
<th>Intermediary</th>
<th>Young’s modulus E [N/mm$^2$]</th>
<th>Poisson Ratio ν [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>70.000</td>
<td>0,2</td>
</tr>
<tr>
<td>Steel</td>
<td>210.000</td>
<td>0,3</td>
</tr>
<tr>
<td>Rubber*</td>
<td>200</td>
<td>0,4</td>
</tr>
<tr>
<td>POM*</td>
<td>2000</td>
<td>0,4</td>
</tr>
<tr>
<td>Aluminium*</td>
<td>70.000</td>
<td>0,3</td>
</tr>
</tbody>
</table>

* The properties for these materials differ a little bit from the earlier presented values, although the differences are minimal
7.2 Results
In this paragraph the goal is to find a relationship between the crack pattern of the experiments of chapter 3 and the stresses in the glass panels, which can be visualized by numerical models. In Appendix G all the figures are shown related to the deformation and the stresses in the numerical models. The figures shown in this chapter summarize the findings of the numerical research, but for an entire overview of the stresses and deformation the figures in Appendix G are helpful.

For materials which have a uniform strength over the entire volume the position where the stress is the highest will be the position where the (initial) crack occurs. For glass the relationship between the crack-pattern and stresses lies a little bit different because the strength of glass is not uniform over the entire volume. The strength of the edges is lower than the strength over the surface of the panels. Furthermore there is quite some variation in the strength at a certain position as well: the edge-strength of float glass varies between approximately 20 N/mm² to 70 N/mm² [25]. This all comes down to defects and the orientation of the defects in the glass panels.

From this it can be concluded that it is not necessarily the case that the initial crack for the glass specimens coincides with the position of the highest stress. When the strength of the glass panels is lower at one position it could be the case that the initial crack will occur at that position although the stress is lower than the maximum stress in the panel. Nevertheless, when the stress is higher at one position, the chance is larger that the initial crack will occur at that position.

Although only 1/8th of the specimens are modeled the figures in this chapter show the stresses in the entire specimen. Because of symmetry in the specimens the figures can be reflected to see the stresses in the entire specimen. The stresses plotted in these pictures are all the maximum tensile stresses (i.e. S1 stresses).
STEEL

In figure 7.4 the initial crack in the glass specimen with steel as an intermediary is visible. Just a small chip broke of the glass specimen in the corner of the panel. Therefor the expectation is that the tension stresses are large in the corners.

In figure 7.3 and 7.5 it becomes clear that almost the entire glass specimen is loaded in compression. Tension stresses only occur in a small area around the edge of the glass specimen in the center of the glass panel and thus also in the corners of the specimen. The presence of horizontal compressive forces in the glass panel, because of the steel intermediary is clearly visible in these figures: the contact surface is totally loaded in compression, because this section is in direct contact with the steel intermediary. The center of the glass panel is not directly in contact with the steel intermediary and therefore the compression forces are smaller and even tension-forces are present in the edges of the glass specimen.

The initial crack occurred for every identical specimen at the edge of the glass panel or to be more precise, in the corner of the glass panel. The corners are the largest areas which are loaded in tension, so the position of the initial crack coincides with the position where the tension-stresses are the highest.
RUBBER

The crack-patterns of the glass specimens with rubber as an intermediary are quite dense (figure 7.7). The glass is crushed in a central part of the specimen and radial cracks are visible from this central part to the edges. Such a dense crack-pattern leads to believe that tensile stresses will be present over a large part of the glass specimen.

The stresses in the figures from the numerical model prove this expectation. The transversal deformations of the rubber intermediary are larger than the transversal deformation of the glass panel, which results in tension forces in the glass panel due to friction (figure 7.6 - left). The tension forces are smaller in the corners because of the prohibited deformation of the rubber intermediary because of its cubic shape: the corners want to deform in two directions at the same time, whereas the deformation in the one direction prohibits the deformation in the other direction. These deformations combined result in a smaller deformation under an angle of 45 degrees. This is clearly visible in the figures in Appendix G. The smaller deformation results in smaller tension forces in the corners of the glass panel.

The tension stresses are smaller in the center of the glass panel (figure 7.6 – right) because the surface is not in direct contact with the rubber intermediary. The corners are even loaded in compression (although the compression is minimal -0,21 N/mm²)

Almost the entire volume of the glass panels is loaded in tension, whereas the tension-forces are larger in the center of the specimen. The position of the initial crack will be somewhere in the center of the panel, which coincides with the resulting crack pattern from the physical experiment (figure 9.7).

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RUBBER INTERMEDIARY:

Maximum tensile stresses (S1) in glass from numerical model

Resulting crack pattern from physical experiment

7.6

7.7

7.8
POM

The crack patterns of the glass panels with POM as an intermediary are also quite dense (figure 7.10), although the pattern differs from the crack pattern of the glass specimens with rubber as an intermediary. Where the crack-pattern with rubber as an intermediary showed a central part where the glass panels were crushed with radial cracks to the edges, the cracks with POM as an intermediary are not radially orientated. The majority of the cracks seem to accumulate at a small distance from the edges of the glass panel. Therefore the expectation is that the tension-stresses are large at a small distance from the edges of the glass panel.

The stresses in the contact surface (figure 7.9 – left) of the glass panel with POM show a small area in the center of the panel which is loaded in compression and increasing tension stresses towards the edge. Again the tension-stresses are somewhat smaller in the corners because of the prohibited deformation of the intermediary as explained for rubber as an intermediary.

The center-surface of the glass panel is loaded in compression in the centre and the edges and zone in-between is loaded in tension (figure 7.9 – right).

In figure 7.11 it becomes clear that the zone for which both the contact surface and the center-surface are loaded in tension is the zone at a small distance from the edges of the glass panel. This is also the zone in which the majority of the cracks seem to accumulate in figure 7.10.
The crack pattern with aluminium as intermediary is also characterised by accumulation of the cracks at some distance from the edges (figure 7.13), but still differs from the crack pattern with POM as intermediary. Where POM also showed a lot of cracks over the entire surface, aluminium only showed cracks at a distance from the edges. Therefore the expectation is that the tension-stresses will be large in the edges of the glass panel.

The stress patterns with aluminium as intermediary are quite similar to the stress patterns with steel as an intermediary. However with steel as an intermediary the contact surface was only loaded in compression, but for aluminium as intermediary the edges are loaded in tension as well (because the aluminium will have a larger transverse deformation than the glass panel) (figure 7.12 – left).

The center surface is mainly loaded in compression although the edges are loaded by a small tension-force (figure 7.12 – right).

With steel as an intermediary only the corners in the center of the glass panels were loaded in tension. With aluminium as an intermediary all the edges (and corners) are loaded in tension for both the contact surface and center-surface of the glass panel (figure 7.14). The cracks accumulate around the edges and stop at the zone where the glass panel is loaded in compression. In the previous models with other intermediaries this behaviour hasn’t been noticed as clearly as in this case, but this behaviour is also known in the case of glass beams [26].
7.3 Conclusion

In this chapter the goal was to find a relationship between the crack pattern of the experiments in chapter 3 and the stresses in the glass panels, which can be visualized by numerical models. The crack patterns are highly dependent on defects and the orientation of defects. Furthermore its unknown how multiple stress directions (which are clearly present in this case) influence the crack patterns. Although the numerical studies presented in this chapter were quite simple and exploratory of nature the zones with maximum tensile-stresses resulting from the models mostly coincided with the initial crack patterns. To be able to fully understand the stress-distribution through the materials in relationship with the crack pattern of the glass panels a more extensive numerical model should be constructed.

Furthermore the effect of the transverse deformations, which were used for the explanation of the results in chapter 3 is also visible in the stresses in the glass panels:

The presence of horizontal compressive forces in the glass panel because of the steel intermediary is clearly visible in the stress-figures: the surface of the glass panel which is in direct contact with the steel intermediary is loaded in compression only. The surface in the center of the glass panel is not direct in contact with the steel intermediary block and therefore the compressive stresses are smaller and at the edges even small tension stresses occur.

With rubber as an intermediary (and the other intermediaries as well) the opposite happens: rubber has a larger transverse deformation than the transverse deformation of the glass panel which leads to tension stresses in the glass. These tension stresses should be larger in the contact surface between glass and rubber, and that is exactly what is visible in the previously presented figures.

From this the results of the experiments in chapter 3 and the explanation of the results, with help of the analytical model, can be verified by the numerical models.
Chapter 8:
CONCLUSIONS &
RECOMMENDATIONS
8 CONCLUSIONS AND RECOMMENDATIONS

Columns are a well-discussed topic in the world of architecture and structural engineering because of the contradicting wishes and desires between architects and structural designers. In general architects and clients do not like columns: they stand in the way and they block the view. If it is impossible to reduce them in number, architects ask them to be made as small as possible. Structural engineers, on the other hand, love columns: they reduce the span of beams and floors and make structures less complicated. To overcome these contradicting wishes and desires with respect to columns, two solutions are available: columns could be made less present, or more attractive. Both these solutions are possible when glass is used for the material of the column.

When a load-bearing glass column is constructed by stacking glass panels on top of each other, the column loses some of its transparency, but it still shimmers, shines, reflects and therefore glass plays with light. Not (only) the transparency, but how glass plays with light fascinates architects from all over the world. However, the knowledge of the structural behaviour of glass columns is insufficiently developed, especially for the stacked column.

To see whether or not glass columns are structurally feasible and to contribute to the development of the knowledge on glass columns the objectives of this graduation project are:

- give insight in the possible configurations and points of attention of glass columns
- conduct experimental research into the load-bearing capacities of glass columns
- conduct numerical research into the load-bearing capacities of glass columns

From all the developed concepts, the stacked column is the most promising concept as far as making use of the high (theoretical) compression strength of glass is concerned: the loads can be introduced in the center of the glass panels, rather than on the edges. And because the strength of the center is substantially larger than the strength of the edges, stacked columns will have a relatively high load-bearing capacity. Furthermore the architectural possibilities of the stacked column are virtually endless, by making variations in the shape and/or size of the basic panel and rotations/translations between the panels. For these reasons the stacked column is selected for further research into the load-bearing capacity.
8.1 Conclusions
For a stacked column three main aspects are important with respect to the load-bearing capacity: First of all the material, glass, itself; secondly the connection of the column with other building components and thus the load-introduction into a stacked column; and a third aspect is the stabilizing strategy for a stacked glass column. These three main aspects are analysed by means of experimental and numerical research and the main conclusions are summarized in the upcoming paragraphs.

8.1.1 Glass
Different types of glass could be used to construct a stacked column. Toughened glass would be able to withstand higher tensile stresses which can occur due to irregularities or defects in the glass or on the surface of the glass. However, when toughened glass is used, an initial crack will result in immediate failure of the entire panel. This and the presence of the roller waves in toughened glass (which will be discussed later on), leads to the choice of float glass for the experiments.

The strength of glass often depends on the edge treatment. Edges which are not treated after cutting are full of micro-cracks (so called Griffith flaws) which seriously decreases the strength of glass [4]. When the edges are ground and polished the micro-cracks are reduced to a minimum and the resulting strength of the glass will be higher. For this reason ground and polished float glass is used for the experiments.

For a stacked glass column the tolerances on the thickness, flatness and roller waves need to be considered. From the research on this subject from Jan Wurm [1] it could be concluded that tolerances on the roller waves and thickness are critical for the stacking of glass panels. The tolerances on the flatness (i.e. local and overall bow) seem to be less critical. For this reason toughened glass is less suitable for the concept of stacking. The tolerances on the thickness can be minimized by using only glass from the center of the large sheets following from production. In such a typical large sheet of glass the minimum thickness is typically apparent in the center of the panel, while the maximum thickness appears close to the edges. The deviations from the nominal thickness are smaller by a factor of 10 in the center of the glass panel, so the glass panels for the column need to be cut from the center of the large glass sheets. The tolerances on the thickness and flatness of the float glass panels used for the experiments for this graduation project are also analysed and verify the research by Jan Wurm:

From the measurements of the thickness it can be concluded that 95% of the glass panels will have (at any given point) a thickness between 11,646 mm and 11,880 mm. The range of the thickness is relatively large, because the small glass specimens are cut from both the center and the edges of large glass sheets following from production. These tolerances are critical and should be minimized by cutting glass panels for the column only out of the center of the large sheets.

The panels used for the experiments in this graduation project are 100 x 100 mm, so within such a small panel the tolerances on the thickness are not critical: 95% of the deviation from the nominal thickness in one glass panel (at any given point) will be between – 0,016 mm and +0,016 mm.

From the measurement of the flatness it can be concluded that these tolerances are not critical either: 95% of the total deviation from the flat surface will be between – 0,026 and +0,026 mm.
8.1.2 Intermediary

The function of the intermediary is to introduce the loads, coming from other building components, into the glass column in such a way that stress concentrations and tension forces do not occur in the top/bottom glass panels. The influence zone of the intermediary is therefore limited to the first (few) top/bottom panels. Important properties of the intermediary are the Young’s modulus, Poisson’s ratio, coefficient of friction, hardness, ultimate strength and homogeneity. For the experiments only homogeneous intermediary materials are selected. Stress concentrations in glass should be avoided at all costs and therefore it is important that the mechanical properties are equal over the entire volume of the material. To ensure a wide variation in other properties the following intermediary materials are selected: steel, rubber, POM, nylon and aluminium.

From the experiments in chapter 3, with a single glass panel between two specimens of the intermediary material, and the numerical research in chapter 7, it can be concluded that steel, surprisingly, is the most promising intermediary material.

Statistical interpretation of five ‘identical’ experiments resulted in a characteristic initial crack stress of \(-209.8 \text{ N/mm}^2\) for steel. The characteristic initial crack stress for steel is twice as high as for aluminium and approximately 10 to 20 times as high as for nylon, rubber and POM. Furthermore the numerical studies showed that the glass panels with steel as an intermediary where almost entirely loaded in compression. In the glass panels with the other intermediary materials, tension-forces occurred over a larger area at substantially lower external stresses.

These results can be explained by the presence of horizontal compressive forces in the glass panels because of the steel intermediary: due to the high Young’s modulus the transverse deformations of the steel intermediary are smaller than the transverse deformations of the glass panel. Subsequently horizontal compression forces are introduced in the glass panel, due to friction between the surfaces of the two materials. Before the ultimate tension-strength is reached the tension forces first have to overcome the compressive stresses, which results in a higher initial crack stress. For the other materials the transverse deformations of the intermediary are larger than the transverse deformations of the glass panels, which introduces horizontal tension forces in the glass specimen, causing the panel to break at much lower stresses.

A negative aspect of a high Young’s modulus is the fact that it cannot easily deform and adapt to the micro-profile of the glass, or other irregularities. In practice this means that the contact-surface between steel and glass needs to be totally flat and it needs to be cleaned thoroughly to make sure no other irregularities (like sand for instance) are present. Even the slightest irregularities can cause the first glass panels to break at much lower stresses.

As described before the influence zone of the intermediary is limited to the first (few) glass panels at the top and bottom of the stacked column. A typical stacked glass column is made up out of hundreds of layers, so the panels no horizontal compressive forces will be present in the central panels of the column, especially when an adhesive interlayer with a low Young’s modulus is used for stabilizing the column. These panels will fail before the top/bottom panels will fail. For a large stacked column, it will be beneficial to use aluminium as an intermediary. Aluminium has approximately the same Young’s modulus as glass and therefore no horizontal tension-stresses will occur in the glass panels. Because the Young’s modulus of aluminium is only one-third of the Young’s modulus of steel, the presence of irregularities (in the surfaces of the materials or external irregularities like sand for instance) is not as big a problem as for steel: aluminium will deform, so no cracks will occur in the glass panels.
8.1.3 Stabilizing strategy

This graduation project focuses on the stabilizing strategy by means of an adhesive interlayer, because it appeared to be the most promising stabilizing strategy, especially as far as safety is concerned: the adhesive interlayer can slow down/stop crack growth and prevent shards of glass from flying around. As for the other stabilizing strategies nothing prevented shards of glass from flying around, which leads to unsafe situations.

Three series of experiments, with stacked columns build up out of different amounts of glass panels, have been conducted with different types of adhesive interlayers and various properties. The goal was to get some insight into the structural behaviour of a stacked column with an adhesive interlayer between the glass panels. The conclusion which can be drawn from these experiments can be categorized into three main aspects: strength, stiffness and stability.

STRENGTH

From the results of experiments B – interlayer (chapter 4) it can be concluded that by means of an adhesive interlayer a higher characteristic initial crack stress can be achieved, compared to a dry stack. The characteristic initial crack stress for the specimen of two glass panels with epoxy adhesive AD821 was 35% larger than the characteristic initial crack stress of the stack of two panels without interlayer (- 83,0 N/mm² versus - 61,1 N/mm²).

Whether or not a higher characteristic initial crack stress will be achieved for a stack of two glass panels with an adhesive interlayer is not dependent on the type of adhesive (acrylate, epoxy or polyurethane).

However, the characteristic initial crack stress is highly dependent on the properties of the adhesive interlayer and the Young’s modulus is the most important property. From the results of the experiments it can be concluded that an adhesive with a low Young’s modulus is the most suitable, because it is able to redistribute the loads over a greater surface, and thereby reducing stress concentrations: the specimens with the three adhesives with a low Young’s modulus (i.e. ranging from 114 N/mm² to 260 N/mm²) had a characteristic initial crack stress ranging from - 66,8 N/mm² to - 83,0 N/mm² for the experiments in chapter 4 (experiments B – interlayer). The two specimens with a high Young’s modulus (i.e. 800 N/mm² and 3000 N/mm²) had a characteristic initial crack stress of - 14,9 and - 54,2 N/mm². The experiments in chapter 5 (experiments C – small stack) verify these conclusions.

When the initial crack stress is reached, this doesn’t necessarily mean that ultimate failure has occurred for the stacked column. From the experiments in chapter 5 (experiments C – small stack) and chapter 6 (experiments D – large stack) it can be concluded that the ultimate failure occurs at a substantially larger characteristic stress compared to the characteristic initial crack stress, provided that the adhesive is able to slow down crack growth: for the most promising adhesive used in these experiments (i.e. epoxy AD821) the characteristic ultimate failure stress for the small stack of five glass panels is approximately 115% higher than the characteristic ultimate failure stress. For the single experiment with a large stack of twenty glass panels the ultimate failure stress was 75% higher than the initial crack stress. From this it can be concluded that a column which is stabilized by means of an adhesive interlayer has a large post-initial crack strength resulting in a safe failure behaviour for the column, providing that the adhesive interlayer can slow down crack growth.
From the same experiments it can be concluded that the adhesive films are not able to slow down crack growth, whereas a liquid application of an adhesive is. For the specimens with an adhesive film as an interlayer an initial crack resulted in total failure of the glass panel and total failure of the entire column. There was no post-initial crack strength, because the interlayer wasn’t able to slow down/stop the cracks from propagating through the specimen. This can be explained by the fact that the adhesive films don’t really cure and don’t form a strong (chemical) bond with the glass panels. A liquid adhesive does cure and does form a strong (chemical) bond with the glass panels and is able to withstand tension-forces (to some degree). Therefore a liquid application of an adhesive is able to slow down crack growth.

STIFFNESS
In traditional columns made out of steel, wood, concrete etc. the stiffness of a column doesn’t really play a role. For a stacked column with an adhesive interlayer in-between the glass panels, the stiffness and the axial deformations do need to be considered, especially when adhesive interlayers with a small Young’s modulus are used. The total axial deformations should not be too large, because when the top point of the columns lowers too much, it is not able to act as a bearing for the other structural elements which are connected to the column. From the results of the experiments in chapter 4, 5 and 6 it can be concluded that the thickness of the adhesive interlayer should be minimized. The axial deformation of an adhesive with capillary action (and thus a thickness of 0mm) is comparable to the axial deformation of an adhesive without capillary action and a thickness of 0,20/0,25mm. So from this point of view it is not extra beneficial to use an adhesive with capillary action.

STABILITY
Stability is always an important aspect for structural elements which are loaded in compression, like columns. Even when stresses are relatively small compared to the ultimate failure stresses, instability problems can occur and columns can be susceptible for (Euler) buckling. Columns with a high slenderness are more susceptible for (Euler) buckling and the stacked glass columns analysed in this graduation project have a slenderness of 8 and lower. Columns with such a slenderness are not expected to be susceptible for buckling, so no research has been conducted into (Euler) buckling of stacked columns in this graduation project.

However, during the last experiment the center of the large stack with the adhesive film as an interlayer swayed to the left. Although this is not (Euler) buckling in the traditional sense of the phenomenon, this observation points to instability problems. In this case it’s more like a central glass panel is pushed out of the layered column due to horizontal forces. The adhesive film does not cure and does not form a strong (chemical) bond with the glass panels and thus the column appears as a layered element. The liquid adhesive AD821 does cure and does form a strong (chemical) bond which results in a more or less solid element. From this it can be concluded that stacked glass columns with adhesive films as an interlayer are more susceptible for instability problems.
OVERALL CONCLUSION ADHESIVE INTERLAYER
From a structural point of view, it can be concluded that from all the types of adhesives the epoxy adhesive AD821 proves to be the most promising type of adhesive for a stacked column which is stabilized by means of an adhesive interlayer:

- The Young’s modulus is low, so the interlayer is able to redistribute the loads over a greater surface avoiding stress concentrations, which results in a high initial crack stress compared to the other types of adhesives.
- The axial deformation is low, because the optimum thickness for the adhesive is relatively low, and so is the standard deviation of the axial deformation.
- The adhesive is able to slow down crack growth, so an initial crack does not result in ultimate failure of the column.
- This results in a high ultimate failure stress compared to the other types of adhesives.
- The ultimate failure stress is substantially larger than the initial crack stress, which results in a safe failure behaviour for the column: lots of cracks are visible before the column collapses, so people can be evacuated and precautions can be made to prevent the column from collapsing.
- The adhesive forms a strong (chemical) bond with the glass panels which results in a more or less solid structural element. This makes columns with this type of adhesive interlayers less susceptible for buckling.

From the viewpoint of aesthetics and the production process an adhesive film will be more suitable, because the stress at which an initial crack occurs is a little bit higher (figure 5.4 and 6.4) and the application of the interlayer is easy and far less time-consuming. However the adhesive film analysed in the experiments shows an unsafe failure behaviour because an initial crack results in ultimate failure of the column and the column is more susceptible for buckling. When, from an aesthetic viewpoint, small cracks are accepted in the column the life-cycle of a column with AD821 can be prolonged because an initial crack does not lead to ultimate failure. Then AD821 would also be the most suitable adhesive from an aesthetic point of view. Whether or not cracks need to be accepted, and to what extent, is a matter of aesthetics and is a question which falls beyond the scope of this graduation project.
8.1.4 Evaluation of the load-bearing capacity of the stacked glass column.
The characteristic value of the initial crack stress and the ultimate failure stress of a stacked column, build up out of hundreds of glass panels, will be smaller than the values presented in this graduation thesis, because of the ‘weakest link in the chain’-effect. Nevertheless it is useful to compare the presented values with the failure stresses for other types of glass columns and columns of other materials.

In part 1 – literature overview some research was presented into other concepts of glass columns. Of these columns experimental research has been conducted into its load-bearing capacity: Eline Ouwerkerk conducted experimental research into the load-bearing capacity of various profiled columns (figure 8.1) [20] and Elke van Nieuwenhuizen et al conducted research into columns made of laminated glass cylinders [27]. The values for the initial crack stress and ultimate failure stress for these columns are summarized in table 8.1 and compared to the results of the experiments with the large stack of 20 panels with AD821 as an adhesive interlayer. The values presented in this table are the result of a single experiment, so these values are no characteristic stresses resulting from statistical interpretation.

The stresses presented in table 8.1 clearly illustrate the potential of the stacked column: the initial crack stress for the stacked column is 3 to 9 times as high as for the other glass columns. The ultimate failure stress is approximately 4 to 7 times as for the other glass columns. A remark needs to be made with regard to the ultimate failure stress: for some other glass columns suffered from instability problems and ultimate failure had occurred due to Euler/torsional buckling. Buckling isn’t analysed for the stacked column, which makes the values more difficult to compare. From these results it can be concluded that the concept of a stacked column is able to make use of the high (theoretical) compression strength of glass. This can be explained by the fact that the loads are introduced over the surface of the panel, rather than the edges, of which the strength is substantially lower.

![Diagram of configurations](image)

Table 8.1 Evaluation of the stacked column compared to other concepts of glass columns

<table>
<thead>
<tr>
<th>Type of column</th>
<th>Dimensions [mm]</th>
<th>Initial crack stress [N/mm$^2$]</th>
<th>Ultimate failure stress [N/mm$^2$]</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stacked column</td>
<td>100 x 100 x 240</td>
<td>-108,1</td>
<td>-190,3</td>
<td>Cracks</td>
</tr>
<tr>
<td>(large stack of 20 panels)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profiled columns (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conf. 1</td>
<td>108 x 108 x 1000</td>
<td>-34,9</td>
<td>-34,9</td>
<td>Cracks</td>
</tr>
<tr>
<td>Conf. 2</td>
<td>116 x 100 x 1000</td>
<td>-29,2</td>
<td>-45,4</td>
<td>Cracks/buckling</td>
</tr>
<tr>
<td>Conf. 3</td>
<td>116 x 100 x 1000</td>
<td>-23,1</td>
<td>-50,8</td>
<td>Buckling</td>
</tr>
<tr>
<td>Conf. 4</td>
<td>143 x 143 x 1000</td>
<td>-26,5</td>
<td>-40,0</td>
<td>Buckling</td>
</tr>
<tr>
<td>Conf. 5</td>
<td>200 x 208 x 1000</td>
<td>-26,0</td>
<td>-26,0</td>
<td>Crack/torsional buckling</td>
</tr>
<tr>
<td>Columns made of laminated cylinders (2)</td>
<td>120 x 1500</td>
<td>-18,0</td>
<td>-57,9</td>
<td>Cracks</td>
</tr>
<tr>
<td>(innerdiameter = 95)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) The values result from a single experiment, so no characteristic stresses resulting from statistical interpretation
(2) For these columns the initial crack stress wasn’t specified. The values for the initial crack stress are extrapolated from the stress-displacement diagrams as the point where a change in the stress-displacement curve is noticeable.
In this paragraph the potential of the concept of the stacked glass column became clear compared to other concepts of glass columns. The potential compared to columns of other materials can be evaluated as well. To do this initial crack stress and ultimate failure stress, resulting from the experiments on the large stack of twenty panels, are compared to the compressive strengths of other materials. These values are based on the results of the single experiment, so the characteristic stresses for a column build up out of hundreds of glass panels will be substantially lower. Therefore the characteristic stresses of the small stack of five panels are also presented in table 8.2.

The values for the initial crack stress and the characteristic initial crack stress for the stacked glass columns are higher than the compressive strength of normal concrete and timber columns and comparable to the compressive strength of high-performance concrete. The ultimate failure stress and characteristic ultimate failure stress of the stacked column are even comparable to the compressive strength of ultra-high-performance concrete. Although the characteristic stresses for a stacked column build up out of hundreds of glass panels will be substantially lower than the values presented in table 8.2 the potential of a stacked glass column are clear.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Failure stress</th>
<th>Characteristic failure stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial crack</td>
<td>Ultimate failure</td>
</tr>
<tr>
<td></td>
<td>[N/mm²]</td>
<td>[N/mm²]</td>
</tr>
<tr>
<td>Glass (stacked column)</td>
<td>Large stack (20 panels)</td>
<td>- 108,1</td>
</tr>
<tr>
<td></td>
<td>Small stack (5 panels)</td>
<td>- 101,0</td>
</tr>
<tr>
<td>Concrete (f'$_{b,rep}$)</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High-performance concrete (HPC)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ultra-high-performance concrete (UHPC)</td>
<td></td>
</tr>
<tr>
<td>Timber (f'$_{c,0,rep}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel (S235) (f$_{y,rep}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) The values result from a single experiment.
(2) The values result from statistical interpretation of five 'identical' experiments.
8.2 Recommendations
As for all research choices have to be made what to analyse and investigate and subsequently not all relevant aspects can be studied. This is also the case for this graduation project and therefore some recommendations are made for further research, categorized for the three main aspects with respect to stacked glass columns: glass, intermediary and stabilizing strategy.

8.2.1 Glass
The glass panels, which are used in the experiments for this graduation project, all had a thickness of 12mm, because this is the largest thickness which is easily available. The thickness of the glass panels need to be considered, because the tolerances on thickness and flatness for instance can be different for smaller/larger thicknesses.

The edges of all panels used for the experiments in this graduation project were rectangular and ground and polished, because research by Fred Veer [bron] showed that this treatment would result in the highest load-bearing capacity. However, the architectural possibilities of this concept are virtually endless when waterjet abrasive cutting techniques are used, which results in other shapes and another edge treatment. The effects of the shape and edge treatment therefore should be considered.

8.2.2 Intermediary
In the experiments of chapter 3 (experiments A – intermediary) steel proved to be the best intermediary material. Because the high Young’s modulus of steel, the transversal deformations are smaller than for the glass panels and horizontal compression-forces are introduced in the glass panels. For the other intermediary materials the transversal deformations were larger than for the glass panels. This results in horizontal tension-forces in the glass panels, which should be avoided.

A negative aspect of the high Young’s modulus of steel is that irregularities (both in the surface of the steel/glass panels and external irregularities like sand for instance) will result in failure of the glass panel, because stress concentrations will occur. Furthermore, the influence zone of the intermediary, is limited to the first (few) panels on the top and bottom of the column. Experiments on large stacks of 20 panels showed that the panels in the center of the panel, which aren’t influenced by the intermediary, will fail before the first (few) panels on the top and bottom will fail. For these reasons for a stacked glass columns, build up out of hundreds of glass panels, it might be beneficial to use an intermediary material with a slightly lower Young’s modulus than glass, like aluminium: the intermediary can adapt to the irregularities between the two surfaces and external irregularities, so stress concentrations in the glass panels are avoided. Experiments on large stacks of glass panels with aluminium as an intermediary should be conducted to see whether the first (few) panels in the top/bottom of the column will fail or the panels in the center of the column.

Normally direct contact between steel and glass is avoided at all cost. The fact that steel proved to be the most promising intermediary for a single panel or small stacks of glass is quite surprising and contradictory with other literature. Further research could be conducted to make use of this finding for stacked columns or maybe even for other structural applications of glass. For a stacked column the load-bearing capacity with alternately glass – steel – glass – steel panels could be analysed.
8.2.3 Stabilizing strategy
As for the stabilizing strategy by means of an adhesive interlayer a wide variety of types of adhesives, with different properties, application systems, curing methods, etc. are analysed. Adhesive manufacturers are constantly improving existing adhesives and developing new kinds of adhesives, so with the knowledge gathered from this graduation project a more focussed selection of other adhesives could be made for further investigation.

In the research presented in this graduation thesis small stacks are investigated and analysed. These ‘compact’ columns (slenderness < 8) will fail when the ultimate (material-) strength is reached, but for columns instability problems also play a role. Additional research would be necessary to analyse the effect of buckling on a stacked column stabilized by means of an adhesive interlayer.

8.2.4 Other relevant aspects regarding stacked glass columns
In paragraph 5.4.5 and 6.4.5 it became clear that polarizer films could be used for a non-destructive quality control. It however is not possible to predict at which stress the panel will fail. So only the position can be defined, not whether or not the column is about to fail. Therefore the non-destructive quality control is only of a qualitative nature, not a quantitative one. Nevertheless this finding is interesting, because for other types of columns these non-destructive quality control procedures hardly exist.

The only aspects of failure which are discussed in this graduation thesis are ‘crushing’-failure of stacked glass columns and buckling of these columns. Some other aspects are important as well from a structural point of view:

The first aspect with respect to stacked columns which is not studied in this graduation project is fire-resistance. Especially when the stacked column is situated indoors and when an adhesive interlayer is used the fire-resistance becomes important: adhesive interlayers in general have a low temperature resistance, which ranges from 80°C to 200°C for the adhesives which are applied in the experimental research of chapter 3-6. How fire will interact with these columns and the adhesive interlayers is important to investigate.

Glass structures are always prone to vandalism, because of its transparent and tactile qualities. So it is important to study how stacked glass columns react to impact loads (intentional or unintentional).

In some of the sculptures of stacked glass panels cracks occurred over time, which could be the result of fatigue. Therefore the column should be exposed to long-term loads and/or dynamical loads.

The above described cracks in some of the stacked sculptures could also be the result of temperature changes or other environmental influences. Especially outdoors columns are under the influence of temperature changes and other environmental influences, which could result in cracks to occur in the glass panels.
Recommendations
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Contact: m.derenet@frencken1901.nl

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Contact: lorenz@sigmund-lindner.com

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Contact: info@sikobv.nl

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Contact: info@technorep.nl

Wilbert de Rooij and Ricardo Ploemen
For helping me with the design and engineering of the demonstration models and with the presentation of these models.
Contact: w.t.d.rooij@student.tue.nl r.ploemen@student.tue.nl
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